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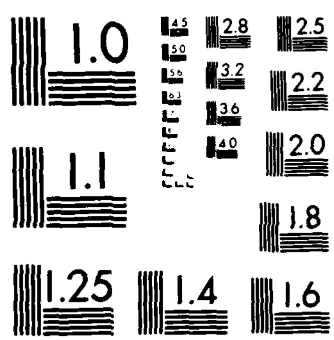
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Report No. CG-D-3-85

AD-A153 845

DEVELOPMENT OF ALTERNATIVES TO THE CURRENT

SAFE POWERING STANDARD

SEPTEMBER 1982

FINAL REPORT

Document is available to the public through the
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Springfield, Virginia 22161

Prepared for

DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20593

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NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
CG-D-3-85	AD-A153 845	

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF ALTERNATIVES TO THE CURRENT SAFE POWERING STANDARD	SEPTEMBER 1982
	6. Performing Organization Code
7. Author(s) IDEAMATICS, INC.	8. Performing Organization Report No.
9. Performing Organization Name and Address IDEAMATICS, INC. 1806 T STREET, N. W. WASHINGTON, D. C. 20009	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. DTCG23-80-C-20003
12. Sponsoring Agency Name and Address UNITED STATES COAST GUARD OFFICE OF RESEARCH AND DEVELOPMENT (G-DMT) WASHINGTON, D. C. 20593	13. Type of Report and Period Covered FINAL REPORT
	14. Sponsoring Agency Code

15. Supplementary Notes

FINAL REPORT SUMMARIZING MATERIALS CONTAINED IN INTERIM REPORT AND ANALYSIS OF SAFE POWERING FORMULA.

16. Abstract A TWO-YEAR STUDY OF ALTERNATIVES TO THE CURRENT SAFE POWERING STANDARD WAS PERFORMED. THIS STUDY INCORPORATES A LITERATURE SEARCH AND REVIEW OF MATHEMATICAL MODELS FOR SMALL BOAT MANEUVERING, A LITERATURE SEARCH FOR DATA ON THE EFFECTS OF ACCELERATION ON UNRESTRAINED PASSENGERS, REVIEW AND REFINEMENT OF A LARGE ACCIDENT DATA BASE, TESTING OF BOAT/ENGINE COMBINATIONS, AND ANALYSIS OF THE RESULTS OF ALL THESE ACTIVITIES.

THE CONCLUSION OF THE STUDY IS THAT AN ALTERNATIVE FORMULA USING MAXIMUM SPEED, A TURN SEVERITY MEASURE DERIVED FROM SLENDERNESS RATIO AND HULL SHAPE, AND THE RELATIONSHIP OF THESE TWO FACTORS TO ONE ANOTHER IS AN ACCURATE PREDICTOR OF THE SEVERITY OF LATERAL ACCELERATIONS GIVEN A PARTICULAR BOAT/ENGINE COMBINATION.

FURTHER ANALYSIS AND TESTING IS RECOMMENDED TO VALIDATE THE FORMULA AGAINST A LARGER DATA SET AND TO REFINE IT TO POSSIBLY INCLUDE A PREDICTOR OF CYCLIC INSTABILITY.

17. Key Words	18. Distribution Statement
BOATING SAFETY REGULATORY PROGRAM BOATING ACCIDENTS LATERAL ACCELERATION SMALL BOAT POWERING TEST PROGRAMS	DOCUMENT IS AVAILABLE TO THE U. S. PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED	181	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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LIST OF SYMBOLS USED

b = maximum chine beam in feet

C = load coefficient

c.g. = center of gravity

F_R = hydrodynamic force on rudder, assumed normal to rudder axis

M' = virtual mass of boat, the mass of the boat plus the hydrodynamic added mass in the lateral direction

p = installed horsepower

P = normal distance from line of action of T to c.g.

r = normal distance from line of action of F_R to c.g.

R = resultant of hydrodynamic forces acting on hull

T = thrust

v = top speed in mph

V_g = reduced speed in turn along tangent to path

w = weight, either specific water weight in lb/ft^3, or total weight of boat and load in lbs (displacement)

x_{cp}, y_{cp} = center pressure of hull hydrodynamic forces

β = motor/rudder turn angle

Δ = displacement in pounds

ϕ = draft angle

ρ = radius

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CHAPTER 1

INTRODUCTION

IDEAMATICS, Inc., has developed an alternative to the current safe powering standard under contract to the United States Coast Guard (Contract Number DTCG23-80-C-20003. This report is the final report. This project is a continuation of an earlier effort (Phase I Research) into the second phase of work: Phase II, Data Gathering, Analysis and the Development of Requirements. Phase II work is further divided into seven specific tasks. These tasks are:

Task 1: Theoretical Studies

Task 2: Data Base Expansion

Task 3: Analysis of the Data Base

Task 4: Development of Alternative and Preliminary Analysis

Task 5: Test Procedure Analysis

Task 6: Testing

Task 7: Preparation of the Proposed Technical Approach

This final report presents the findings of the project described in the following chapters:

Chapter 1: Introduction, background, and methodology. The history of the project is given, its historical background, and in its conception and implementation.

Chapter 2: A review of mathematic analysis of boat design considerations. Analytical procedings are discussed, along with certain available literatures.

Chapter 3: Examination of the effects of acceleration on humans. Applicable research reports are discussed, and connections made between research findings, representational recreational boating scenarios, and actual boat testing data.

Chapter 4: Review of PRAM study.[1] Techniques of data treatment are discussed. This chapter includes all final analysis of PRAM data, and the links between those data and the boat testing program.

Chapter 5: Description and analysis of testing program. The test courses are described, as are the boats, engines, and recording instruments. Methods of data recording, reductions, and transcriptions are enumerated, and final data reporting sheets are described. Results are then analyzed, the analysis including description of data processing techniques. Individual boat test summaries are included, and a review of project activities is appended.

Chapter 6: Analysis procedures summary, formulae development, and validation. An approach for predicting speed, turn severity and acceleration is presented. The application of the approach is reviewed.

Chapter 7: Proposed Technical Approach. The recommended development of a revised standard is summarized.

Chapter 8: Advanced Development Plan. A procedure for advancing the new standard is outlined.

BACKGROUND

The Federal Boat Safety Act of 1971 (46USC Sec 1451, et seq.) greatly expanded the responsibility and authority of the Coast Guard in the area of recreational boating safety. 46USC Sec. 1451 authorizes the Coast Guard to establish minimum safety standards for boats and their associated equipment and specifies that each standard must be reasonable, meet the need for boating safety, and be stated in terms of performance, as far as practicable.

Pursuant to that authority, the Coast Guard, in 1972, established a safe powering standard for monohull boats less than 20 feet in length

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1 "PRAM" stands for "Powering Related Accident Model." The PRAM data base is a set of 465 recreational boating accident reports amassed by the Coast Guard in 1975 and 1976. These accidents were initially isolated and analyzed in A Study to Determine the Need for a Standard Limiting the Horsepower of Recreational Boats, by R. W. White, C. Stiehl, N. Whatley, and W. Blanton of Wyle Laboratories, 1978, USCG Report No. CGD-36-83.

powered by outboard motors (33 CFR, Part 183, Subpart D.). The standard was one previously established by the boating industry and published in ABYC H-26.[2] It was based on a limited sample of outboard boats and was thought to be conservative.

This standard, still in use, sets allowed horsepower capacity based on simply measured boat parameters: length, transom width, transom height, presence or absence of remote steering, and nature of bottom (flat bottom, hard chine or other). Its application has resulted in some freak "rule-beaters" (e.g., by sharply raking the bow to increase length and thereby the formula capacity). White et al.,[3] on the basis of data accumulated in five different test programs, suggest that the formula method of the existing standard provides only an average value of horsepower capacity. Manufacturers and designers feel the present standard is too conservative.[4]

Due to the substantial amount of research and development in the area of safe powering since the promulgation of the present standard, fuller grasp of the problem and pertinent phenomena is possible. Therefore, the Coast Guard contracted IDEAMATICS, Inc., to perform an evaluation of the current safe-powering standard.

IDEAMATICS' task was to evaluate the safe powering measurement state-of-the-art, to propose alterrate standards for development and, ultimately, to recommend promulgation of a new regulation. The scope of the task was to address monohull boats of less than 20 feet in length with inboard/outboard (I/O) as well as outboard (OB) propulsion.

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[2] ABYC H-26, 1973-74, Powering of Boats, SAFETY STANDARDS FOR SMALL CRAFT, American Boat and Yacht Council, Inc.

[3] White, R.W., Bowman, J.O., and Patrick, S.L., Standards Analysis -- Powering/Performance Evaluation Using Test Course Methods, 2 volumes, USCG Interim Report, Wyle Laboratories, March 1974.

[4] Bass Boat Powering Test Course Evaluation -- Preliminary Report, Wyle Laboratories, 20 November, 1972.

The previous Interim Report published under this contract presented a review of the literature applicable to the safe powering problem, a mathematical analysis of maneuvering, and an analysis of the Powering Related Accident Model (PRAM) data base. An accompanying Data Report compiles all of the data gathered during the course of the project. This Data Report is incorporated as a reference for the Final Report.

METHODOLOGY

The organization of this final report reflects the progress of the entire project, in that it presents preliminary research, the testing based on that research, conclusions drawn from the testing, and suggestions for the development of potential standards. The organization is presented in the following section and depicted in Figure 1-1, Powering Analysis Flow.

Identify Accident Categories

As part of the background research, IDEAMATICS performed an intensive study of the Powering Related Accident Model data base (PRAM). The focus of this research was to classify actual powering-related recreational boating accidents according to type. This was achieved by means of an examination of the set of Boating Accident Reports (BARs). From this examination, analysts determined what accidents could be grouped together according to type, that is, whether the accident might have been caused by inherent instability of the boat, the boat's interaction with the environment, a collision, or an electrical or motor-related problem. IDEAMATICS developed an accident classification scheme, which was reviewed and modified to identify accidents more rigorously than did previously existing schemes. At

POWERING ANALYSIS FLOW

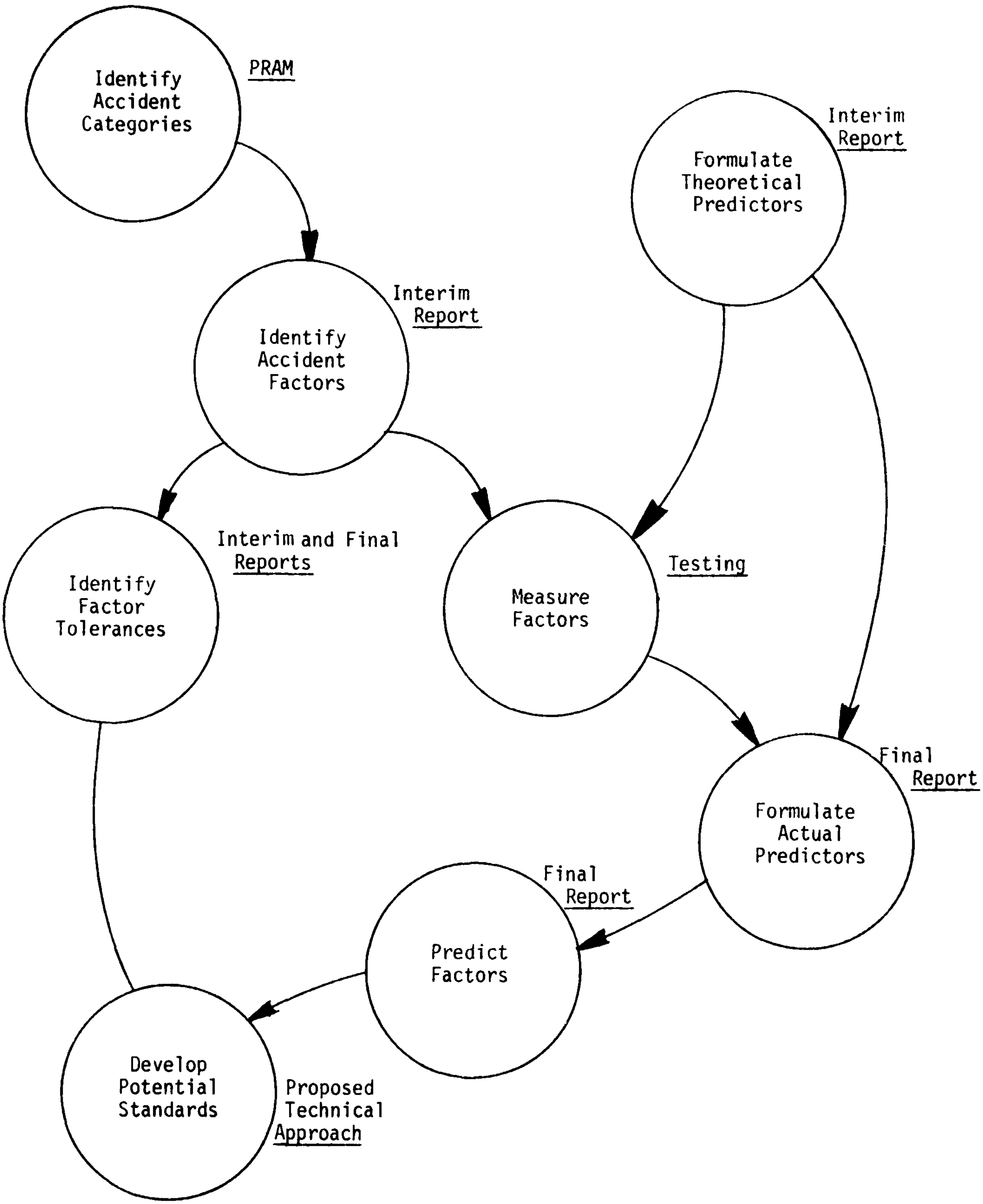

Figure 1-1

the same time, measurements (length, beam, hull shape, etc.) were ascertained for each boat involved in an accident. The data base was then augmented by a number of additional measurements.

Identify Accident Factors

Once the accidents were arranged according to similarity of events, analysts identified causative factors in the accidents. In arriving at the accident factors, analysts reduced accidents to physical components, subdividing the actual train of events during accidents into types of motion, that is, into kinematic, cyclic, maneuvering, and stability factors. Each BAR was reexamined for applicability to the revised classification scheme, which stressed boat performance rather than operator error or environmental influence. Classification was made according to major accident factors and subfactors within each one of these groups. Non-boat-related accidents were rejected from the study, and attention was centered on those characteristics of boat performance which might lead to accidents. A scenario was written for each accident type.

Formulate Theoretical Predictors

Theoretical research for the project was pursued in two areas: mathematical description and acceleration studies. In both areas, an intensive search was made of the relevant existing literature. In the mathematical area, this research was the basis for conjectural discussion of various formula approaches to the problem of describing the motion of a recreational boat in the water. In the acceleration area, background research led to the creation of an acceleration matrix and formulation of a scale of acceleration tolerances for recreational boats. This matrix compares various judgments concerning the tolerance of the human body to

differing acceleration levels at which discomfort is felt, balance is lost, muscular activity is restricted, etc. With the performance of these two research tasks, analysts were able to formulate theoretical predictors for recreational boating accidents.

Identify Factor Tolerances

By synthesizing information from the PRAM study and the theoretical research, analysts identified factor tolerances. Accident scenarios were compared to accelerations identified on the acceleration matrix as causing certain kinds of inhibition of muscular motion or actual physical displacement, and estimates were made concerning the amounts and sorts of acceleration forces which must have been exerted during each type of accident. These conjectures were later compared with acceleration data obtained from the testing program. Physical behavior of small boats was analyzed in light of the comparison of these three corroborative kinds of data (the PRAM accident scenarios, the acceleration matrix, and the test acceleration data), and a clear subdivision of boat behavior made.

Measure Factors

Theoretical research was documented in the Interim Report and formed the basis for the next step, the Testing Program, which is presented in detail in the Tests Results Report. During this step of the project, IDEAMATICS conducted tests on a sample of small boats in an effort to replicate the types of boat behaviors which might, in actual practice, lead to hazardous situations or which might predict the ability of the boat to avoid the same. A number of boat/engine combinations, each instrumented to record data, were run through a series of test courses. Data obtained from the various recording instruments in the form of films, strip charts, radar-

gun readings, magnetic voice recordings, and verbal observation were all transcribed to data sheets, standardized, and keyed into a computer data base for analysis.

Formulate Actual Predictors

Synthesizing the data from the PRAM studies, theoretical studies, and testing program, IDEAMATICS formulated predictors of the postulated factors. For this step, data bases created in previous steps were statistically analyzed. Mean acceleration forces derived from the testing data were compared with those acceleration forces identified in the PRAM studies and the theoretical research as dangerous. Individual boat test behavior summaries were made, and various juxtapositions of boat performance and boat parameters made in order to determine correlations between physical measurements of boats and behavior. High correlations enabled analysts to spot areas in which mathematical equations might be used to describe behavior. Various equations were modelled and their validity tested using the data bases.

Predict Factors

Using the equations now formulated, analysts can predict the accident factors. This method allows us to determine the magnitude of the forces which have been shown to cause accidents. With the equations in hand, analysts took the formula and went back and checked each boat's performance against the new predictors, as well as against the existing formula and the ABYC test. This method has enabled us to extrapolate, from actual performance, data which may then be used predictively.

Develop Potential Standards

With an ability to predict the magnitude of forces contributing to recreational boat accidents, it is possible to formulate a Proposed Technical Approach to aid in the control of those forces. This Approach suggests ways in which to validate the new formulae by means of testing them on a new set of boats. The new test program enables us to see whether we can use the equations developed to predict the performance of any small boat. Having applied it to the boats already tested, we must validate its application to any future testing for performance rating.

The formulation of this Approach is the foundation for the Advanced Development Plan, which is designed to implement the resultant standards. The Advanced Development Plan outlines a method of implementing the Proposed Technical Approach. The validation of this study by comparison against a broader boat universe will take the form of an expanded boat testing program.

Final standards will be promulgated after review and comment from the boating industry and the boating public.

CHAPTER II

MATHEMATICAL ANALYSIS OF THE MANEUVERING PROBLEM

There are several approaches to setting a standard for safe powering levels for small recreational boats: formula, performance rating tests, analytic and empirical determination. This chapter summarizes various mathematical approaches to analyzing small boat maneuvering. A fuller treatment may be found in IDEAMATICS' Interim Report.

DISCUSSION OF THE PRESENT STATE-OF-THE-ART

The following sections discuss state-of-the-art mathematical analysis techniques for various factors in small boat maneuvering.

Speed, Trim Angle, and Porpoising Factors

The state-of-the-art of predicting speed and power relationships for larger planing craft is well advanced. The empirically based methodology includes computation of the effects of appendages and trim tabs, the interaction of propellers and hull, and the resistance added by rough water. All of this activity is, however, for straight-ahead running. There is very little in the literature concerning performance during maneuvering.

There is a problem in translating the methodology to the small boat field. The methodology is empirically based, and the data come predominantly from prismatic hull shapes that are heavily loaded. However, small recreational planing boats are much more lightly loaded. For example, Savitsky, Blount, and Fridsma based their findings on boats whose load coefficient[1] ranged from 0.3 to 0.9, while White, Bowman, and Patrick analyzed boats whose load coefficient averaged 0.1, which is typical of the boats studied for powering standards.

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[1] A load coefficient is defined as: $C_\Delta = \Delta/wb^3$

where: Δ = displacement in pounds
w = specific water weight in lb/ft^3
b = maximum chine beam in feet

Another problem in applying the methodology is that the small boat field is characterized by a wide variety of hull shapes, many of which differ radically from the prismatic or nearly prismatic shapes typical of larger craft. It is clear that the hydrodynamic lift and drag relationships for, say, a tri-hull will not be the same as for a V-hull. Nonetheless, the methodology is available. What is required is to examine the available data for small boats to determine the applicability of the methodology, and then to expand the empirical methodology where needed.

With respect to speed prediction, an effort was made to determine maximum boat speed given various hull and power characteristics in Reference 30. Data for 277 boats were available from performance test reports of the Mercury Marine Division of Brunswick Corporation. In Reference 20, an exploratory analysis was made of the following relations:

Crouch's formula:

$$v = K(Hp/w)^{\frac{1}{2}} \qquad (1)$$

$$v = \frac{Hp \times Pitch}{Weight} \times C \qquad (2)$$

$$\tfrac{1}{2}w/g\ (v)^2 \text{ vs. } Hp \times Pitch \qquad (3)$$

$$v(w)^{\frac{1}{2}} \text{ vs. } Hp \qquad (4)$$

where v = top speed in mph
p = installed horsepower
w = total weight of boat & load in lbs. (displacement)
C = load coefficient

(K, x, and y are coefficients determined by performing a multiple regression fit to the Mercury data.) It was felt that none of the relations gave a reasonable prediction of speed.

Crouch's formula is widely used by designers in making estimates of required horsepower at the preliminary design stage. The constant K varies

with hull shape, and may be thought of as a measure of the relative efficiency of the shape.

In preliminary work on this project, IDEAMATICS drew on the same Mercury data base used in Reference 30 and used a statistical computer program, SAS, to perform multiple regressions in deriving a speed/power relationship.

The expression used for the model is:

$$v = K \frac{p^x}{w^y}$$

The expression is given in a note by Gill, appearing in Reference 21. He attributes the form to Eugene Clements, and says it is the most generally useful he has found.

The Gill/Clements formula used by IDEAMATICS on the Mercury data was estimated in log-linear form through multiple linear regression. Through transforming the dependent variable (speed) and the independent variables (horsepower and load) into natural logs, the non-linear form of the formula is transformed into a linear equation. The linear equation's coefficients are estimates of the constants in the Gill/Clements Equation.

The results of the regression fitting are presented in Table 2-1. The R^2 values in the table provide a measure of how much variation in the dependent variable, speed, can be accounted for by the model. R^2, which can range from 0 to 1, is the ratio of the sum of squares for the model divided by the sum of squares for the corrected total. In general, the larger the value of R^2, the better the model's fit. A value of .8 or better is thought to represent a good fit. As can be seen from Table 2-1, the R^2's are good.

Figure 2-1 is a plot of Top Speed vs. Installed Power, with Weight as a parameter, for the equation with the coefficients found for all hull shapes combined. In examining the plot, one should keep in mind that speed is the

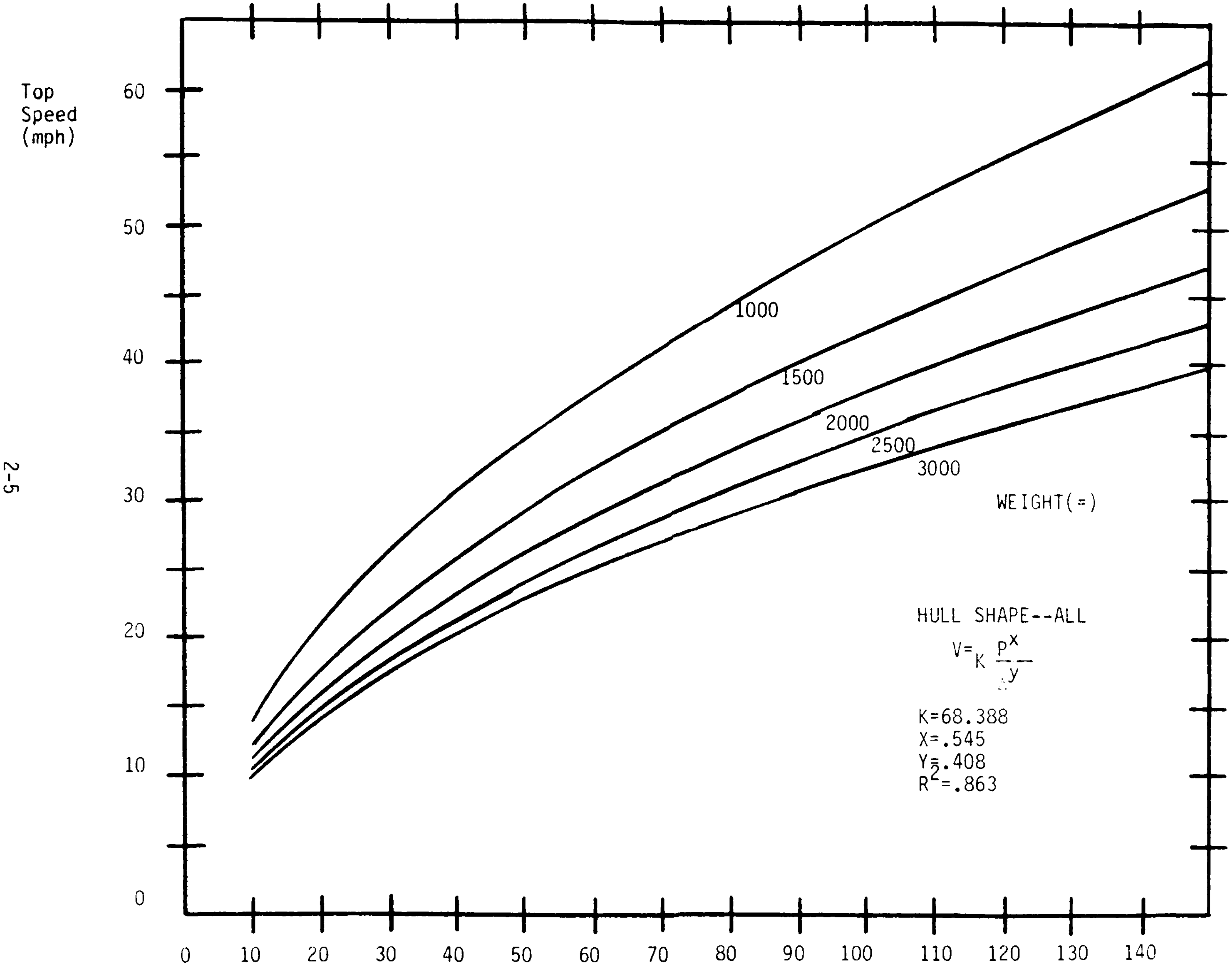
Model: $V = K \dfrac{P^x}{W^y}$

Crouch's Formula: $V = K \left(\dfrac{P}{W}\right)^{\frac{1}{2}}$

HULL SHAPE	SHAPE #	# of HULLS	CROUCH's K	MODEL K	MODEL X	MODEL Y	MODEL R^2
	1	22	174.7	144.5	.513	.483	.93
	2	144	161.6	71.9	.538	.414	.82
	3	51	165.7	62.9	.495	.362	.91
	4	8	176.6	177.5	.604	.564	.99
	5	55	161.8	109.0	.712	.557	.83
	6	125	161.7	56.8	.456	.329	.79
OTHER	ALL	406	159.0	68.4	.545	.408	.86

REGRESSION COEFFICIENTS FOR TOP-SPEED-POWER-WEIGHT MODEL

TABLE 2-1



TOP SPEED VS. INSTALLED POWER
Figure 2-1

predicted maximum top speed of the boat. The shape of the curve is not representative of the speed/power curves of a particular boat; it merely gives the end points of such curves.

Examination of the coefficients x and y in Table 2-1 reveals that for each of the hull shapes the speed is relatively more sensitive to changes in installed power than to changes in weight. The Crouch formula assumes an equal sensitivity. The Gill/Clements form used here is probably more realistic. For comparison with the familiar Crouch coefficients, the average K for both loads for the 14 cathedral hulls in Table IV, App. f, Ref. 30, is 168. A sampling of the deep-V hulls from the Mercury data base gives an average K of 171. Use of the Gill/Clements formula with the regression coefficients derived from all the hull shapes in the course of reviewing the test literature in this work has given good calculated speed values when compared with the reported measured speeds. In no case has the error exceeded 10%.

Roll/Yaw Oscillations

Fast boats may exhibit a relatively quick roll oscillation in either the straight-ahead or turning condition. Often, because of coupling between roll and yaw, a yaw oscillation will accompany the roll. This instability, in its mildest manifestation, is often called "chine-walking" or "hunting." In the extreme case, the oscillations can result in a loss of directional stability and thus in a "spinout," or even capsize. The roll instability probably appears because the shape of the hull is such that relatively large fluctuations in the transverse location of the center of pressure are caused by small perturbations in the roll angle. A yaw movement can be induced, leading to the spinout or capsize, when the roll angle changes the shape

presented to the flow of water. There is no theory available that will predict chine-walking.

Porpoising, i.e., the combined oscillations of a boat in pitch and in heave, of sustained or increasing amplitude, occurring while planing in smooth water, is a similar phenomenon. Reference 26 presents a curve by which the inception of porpoising may be determined for boats of the class covered by that reference. It remains to verify the applicability of the curve to the boats typical of small recreational types or to adjust the curve to fit such boats.

Turn Radius

The turn radius of a boat is an important measure of its ability to turn to avoid collision. There is a trade-off: a small radius can produce uncomfortable or dangerous lateral accelerations on the occupants; a large radius can lead to collision. The turn radius for varying speeds and motor turn angles, if known, can give valuable insight into the magnitudes and directions of the hydrodynamic forces and moments acting on the hull. This is so because in a steady-state turn the forces and moments are in equilibrium, unlike the constantly varying case that exists when a boat is running an ABYC/BIA type course. A survey of the literature concerning small boat turn radius (see Appendix A) reveals little work. That work which has been done is inadequate to our purposes.

We can begin to develop an expression of the turning radius, ρ, that gives a starting point for planning experiments and analyzing the effect of various factors on the radius, by looking at the forces acting on the hull. See Figure 2-2. When the motor is first turned to the fixed angle for the turn, the boat's center of gravity (c.g.) executes an initial S-curve which becomes a spiral of decreasing radius of curvature, and then enters the

steady-state circular turn, with forces and moments in balance. For high speed planing craft, the transition period to the circle is quite short. Because of the vectored thrust of an outboard, the initial rolling and yawing moments will be counteracted by the build-up in dynamic pressure from decreasing deadrise on the side toward the turn, and, to a lesser extent, by the centrifugal effect of the lateral acceleration acting at the c.g. Because of the drift angle, ϕ, the flow is no longer along the centerline; consequently, there are tangential and normal hydrodynamic forces that cause the boat to assume the circular path. The ability to develop the normal force component is important to prevent a skidding, large-radius turn.

In order to derive turn radius, ρ, the force and movement equations must be developed. First, define the x, y, z orthogonal axis system with origin at the c.g. as follows: fixed in the boat with the x axis in the center-line plane, positive forward, and parallel to the keel/baseline. The z axis is positive downward and parallel to earth vertical; the y axis is positive to starboard. In short, the system is rotated from the normal boat system by the roll angle, which is constant in a steady-state turn.

The force and moment equations then are:

$$T\cos\beta - F_R\sin\beta - M'V_g{}^2/\sin\phi - R_x = 0 \qquad (6)$$

$$-T\sin\beta - F_R\cos\beta - M'V_g{}^2/\cos\phi + R_y = 0 \qquad (7)$$

$$F_R p + R_x y_{cp} - R_y x_{cp} + Tr = 0 \qquad (8)$$

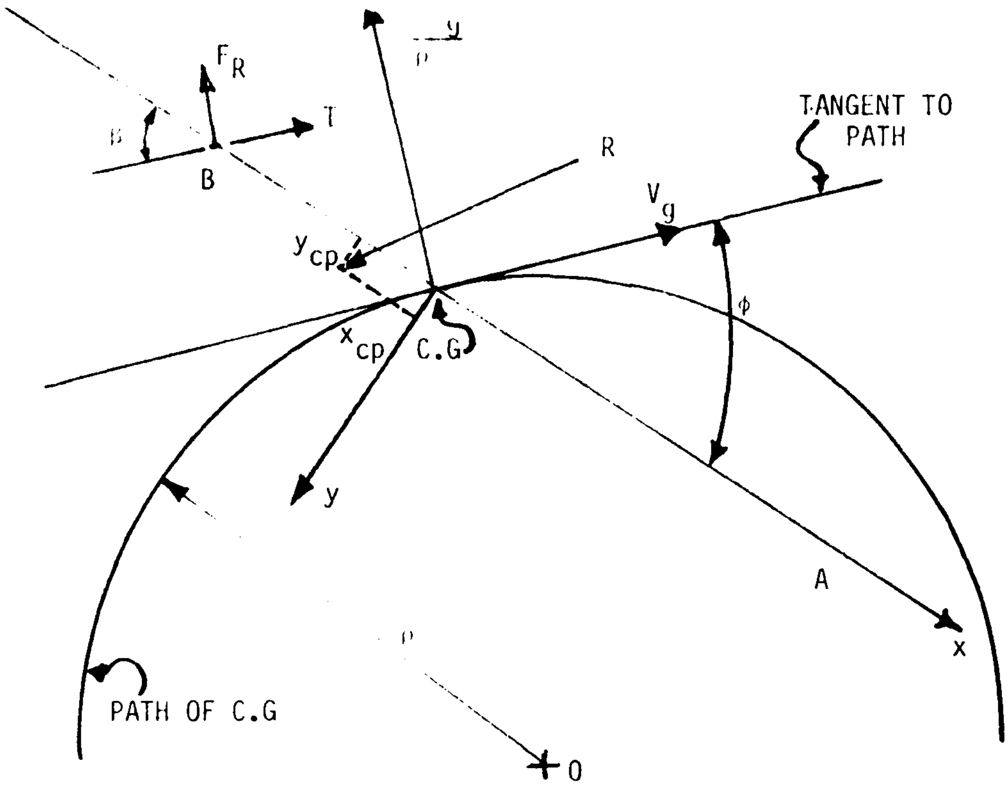
where: R_x and R_y = x and y components of R
(Other symbols are defined in Figure 2-3, Forces Acting on the Radius)

Solving (9) and (10) for R_x and R_y, substituting into (8), and solving for ρ we get:

$$\rho = \frac{M'V_g{}^2(x'_{cp})}{T(r + y''_{cp}) + F_R(p - x''_{cp})} \qquad \text{(Eq. 1)}$$

where: $x'_{cp} = x_{cp}\cos\phi + y_{cp}\sin\phi$

$x''_{cp} = x_{cp}\cos\beta + y_{cp}\sin\beta$



M' = virtual mass of boat, the mass of the boat plus the hydrodynamic added mass in the lateral direction

R = resultant of hydrodynamic forces acting on hull

x_{cp}, y_{cp} = center pressure of hull hydrodynamic forces

F_R = hydrodynamic force on rudder, assumed normal to rudder axis

[illegible] = normal distance from line of action of F_R to c.g.

T = thrust

r = normal distance from line of action of T to c.g.

V_g = reduced speed in turn along tangent to path

β = motor/rudder turn angle

ϕ = draft angle

ρ = radius

FORCES ACTING ON THE RADIUS

Figure 2-2

$$y''_{cp} = y_{cp}\cos\beta - x_{cp}\sin\beta$$

It is of interest to note that x'_{cp} is the x coordinate of the center of pressure in an axis system that is rotated to be tangent and normal to the circular path, while x''_{cp} and y''_{cp} are the x and y coordinates of an axis system rotated to be parallel to the rudder/motor axis.

References 26 and 27 give an estimate of x_{cp} for the more heavily loaded planing craft. A systematic series of tests with typical recreational boat hulls in the model tank would probably give good data for estimating x_{cp}, y_{cp}. T, r, F_R, and P can be determined within the present state-of-the-art. V_g can be measured during turning tests, and an empirical relation can be developed for loss of speed during a turn. The virtual mass can be estimated or a relationship between virtual mass and boat shape and attitude can be established in a model basin. The motor turn angle and the drift angle are quantities such that it is not immediately apparent how to derive or develop expressions to use as predictors. Further analytical development coupled with test data, including the drift angle, should provide better insight.

CONCLUSIONS

At the beginning of this chapter, there is an identification of those powering-related maneuvering characteristics that affect safe operation. That list can be compressed into the following criterion: a particular boat, having a specified horsepower available, over its operating range should exhibit the following characteristics:

- o Adequate transverse stability against capsize;
- o No roll or yaw oscillations;

- A suitable running trim such that there is no porpoising, the boat planes, adequate lookout is possible, and no roll or yaw instability appears;

- A suitable turning radius such that a collision can be avoided without excessive lateral accelerations, and such that no loss of directional control occurs.

CHAPTER III

REVIEW AND INTERPRETATION OF ACCELERATION RESEARCH FINDINGS

In performing its study of the current Safe Powering Standard, IDEAMATICS posited that acceleration, particularly lateral acceleration, would have significant effects on persons on board a boat during maneuvering. In order to study these effects, IDEAMATICS first performed library research to develop baseline matrices of acceleration effects at various g levels, and then instrumented test boats to determine acceleration levels during boat maneuvering.

In this chapter, the library research techniques and research results presented in the Interim Report are briefly summarized. The acceleration matrices developed through the research are related to the PRAM dynamic stability scenarios.[1] Finally, the maximum accelerations obtained during boat testing are related to the acceleration matrices.

ACCELERATION RESEARCH

IDEAMATICS researched the physiological, psychological, and mechanical effects of acceleration on unrestrained vehicle passengers. The purposes of this research were to gain a sense of how passengers react to various types and degrees of acceleration, and of when these accelerations become actively dangerous.

It proved unproductive to research boat passenger acceleration directly; few tests have been performed measuring the accelerations produced by boat maneuvering. Rather, IDEAMATICS' researchers obtained public transit, automobile, and biomedical information applicable to boating

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[1] PRAM scenarios are to be found in this chapter on pages 3-12 to 3-14, following the acceleration matrices.

situations. The acceleration data obtained are grouped into three levels of severity: the accelerations at which passengers are comfortable, the accelerations at which passengers begin to be shifted about, and the accelerations at which passenger movement becomes difficult as the passenger must concentrate all efforts on resisting the effects of the high accelerations. The discussions of acceleration also yielded information about psychological factors involved in acceleration perception, the types of seating arrangements which best protect (and, conversely, do not protect) unrestrained passengers during different kinds of acceleration, and the effects of acceleration on drivers' abilities to perform the actions required to operate a vehicle.

Research Methodology

Standard library research techniques were used with good success to obtain the acceleration data. These techniques included a search of the National Highway Traffic Safety Administration's computerized files, as well as a search of book and periodical holdings catalogues. Such keywords as "acceleration," "public transit safety," "passenger safety," "boating--accidents," "buses--accidents," "automobiles--accidents," "motor vehicles--accidents," and "public transit--comfort" were searched, resulting in a list of approximately 200 items to be investigated. In addition, periodic guides to literature and guides to Federal Government technical reports were consulted.

When sufficient material had been assembled, IDEAMATICS' researchers began the task of reading quickly through the literature. It was expected that most of the 200 items on the list would be tangentially applicable

only, and this proved to be the case.[2] However, a number of good information sources were discovered, and the bibliographies contained in these documents provided additional information sources.

As a rule, IDEAMATICS' researchers constructed an abstract of all sources with applicable information, and made careful note of the acceleration data. Only a bibliographic note was kept for sources which were of no assistance for this project.

Facilities Used

IDEAMATICS used a number of Washington, D.C., research facilities for performing the acceleration research. These included:

- o Department of Transportation main library;
- o Department of Transportation branch library (FAA);
- o Library of Congress;
- o National Highway Traffic Safety Administration reading room;
- o American University library;
- o Arlington County Public Library; and
- o David Taylor Naval Research and Development Center library.

Caveats on Use of the Data

The information assembled in the matrices comes from a number of different sources, reporting research results in areas as different as light aircraft seat design and school bus safety. Therefore, the data assembled in the matrices must be used with care. This is especially true of the

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[2] For example, articles discussing acceleration effects on restrained car passengers in a rear end collision were not applicable because (1) the passengers were restrained by air bags, and (2) the decelerations reported were extremely high. Other documents discussed modeling of passenger behavior without providing acceleration values; others were too limited in scope.

subjective data on comfort. Gebhard[3] reported, for example, that comfortable lateral acceleration levels for public transit vehicles were much lower than those for automobiles, and speculates that this is a result of both seat design (bench-type seating in public transit vehicles vs. bucket seats in automobiles) and passenger expectation (automobile passengers simply expect higher lateral accelerations during turns).

The other caveat on use of the acceleration data matrices for boating safety analysis is that the data do not refer to a boating environment. For example, a turn on a public transit vehicle may be perceived as more uncomfortable, and may move unsupported passengers sooner, than an equivalent turn in a boat, because the boat "banks in" to the turn while the public transit vehicle does not. Furthermore, the degree to which a boat may be said to make a coordinated turn varies greatly with its hull configuration. Boats with deep-V hulls perform well coordinated turns, while boats with flat bottoms perform poorly coordinated turns. In general, the interactions of a boat with water are more complex than the interactions of a land vehicle with the surface it travels over. In addition, data do not distinguish between steady state and sudden, transient accelerations.

Despite such problems with the data, they do provide a fair baseline of lateral, longitudinal, and vertical acceleration effects. They are best interpreted as suggested ranges rather than as absolute, defined points.

Nature of the Data

Data were obtained for longitudinal, lateral, and vertical acceleration (including deceleration). The largest amount of information was available

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3 Gebhard, J.W., Acceleration and Comfort in Public Ground Transportation, Transportation Programs Report, Johns Hopkins University Applied Physics Lab, for U.S. Department of Transportation, February 1970.

for longitudinal acceleration and deceleration. Vertical acceleration information w.s divided between vibration (short-duration vertical acceleration) data and extremely high g data (light plane crashes and ship shock motions). The data may be divided roughly into three classes. The first is comfort data, detailing the acceleration level at which passengers are comfortable and identifying the point, for each type of acceleration, at which discomfort sets in. The second is motion data, defining the acceleration level which is required to move an unrestrained standing or sitting passenger off his/her feet or seat. The third category is physiological function data, detailing the acceleration level at which voluntary passenger motion is barely possible and at which the effects of acceleration begin to interfere with an operator's ability to drive a vehicle. These data are provided in three matrices, which are presented and discussed in the following sections.

Acceleration Matrices

The acceleration matrices present data for longitudinal, lateral, and vertical acceleration. The matrices are designed so that the effects of increasing acceleration may be ascertained by reading the "Effect" column. Each matrix is discussed ndividually in the following sections.

Longitudinal Acceler.tion Matrix

The longitudinal acceleration matrix begins with levels at which longitudinal acceleration is perceived as comfortable by public transit passengers. The data are subjective, based on passenger responses to the experimenter's questions. The next data set in the longitudinal matrix reflects objective measurements of the points at which standing and seated passengers are dislodged by deceleration. There is a range of almost .1 g between the upper comfort limit for seated passengers and the point at which

a supported standee begins to lose his/her balance. However, there is much smaller range for unsupported standees. In that case, there is only .01 g difference between the upper comfort level of seated passengers and the point at which an unsupported standee begins to lose his/her balance. This low difference may be significant in the boating environment; since few standees in boats have supports available to them, what a seated passenger perceives as comfortable may cause a standing passenger to fall. The next set of longitudinal acceleration figures provide the upper limits of motion for persons under high acceleration. Such high acceleration will seldom be encountered by boat operators and passengers, but the information is included in order to provide a complete range of effects for longitudinal acceleration and deceleration.

Lateral Acceleration Matrix

Fewer data were available for lateral acceleration. However, a substantial amount of work has been done in the area of public transit, because lateral accelerations are likely to unseat bus or subway passengers if the acceleration is too extreme. These public transit data are readily transferable to the boating environment, since the seats of public transit vehicles are similar to the unupholstered seats found in small boats (e.g., johnboats). The matrix begins with anomalous data. Dunlop[4] and Gebhard[5] cite two quite different figures for acceptable levels of comfort for lateral accelerations. These data are subjective, which may explain the different levels. The same relationship which exists between longitudinal discomfort and dislodgement of a free-standing passenger exists for lateral acceleration. 0.23 g of lateral acceleration was perceived as

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4 Dunlop & Associates, Development of Techniques and Data for Evaluating Ride Quality, Volume I, Summary; Volume II, Ride Quality Research, 1978.
5 Gebhard, op. cit.

uncomfortable; a free-standing passenger is dislodged by 0.3 g of lateral acceleration. The upper ranges of lateral acceleration effects are represented by the last two entries in the matrix. Of particular interest is the United States Air Force statement that 2 g is the limit for "effective" movement under lateral accelerations. "Effective" was defined in the report as quick movement which accomplishes tasks without undue effort. Again, no distinction is made between short, sudden accelerations and those of lasting duration.

Vertical Acceleration Matrix

The vertical acceleration matrix presents the riding comfort ranges (from very good to intolerable without restraint) of vertical vibration in public transit.

ACCELERATION MATRIX: LONGITUDINAL ACCELERATION

g Force (Longitudinal)	Effect	Source
0.11 - 0.15 acceleration	comfortable longitudinal acceleration for public transit	Gebhard
0.16 deceleration	unsupported standee loses balance in bus	DOT, Deceleration Effects
0.2 deceleration	safe for seated subjects	DOT, Deceleration Effects
0.23 deceleration	Strap-supported standee loses balance	DOT, Deceleration Effects
0.27 deceleration	vertical stanchion-supported standee loses balance	DOT, Deceleration Effects
0.94 deceleration	dislodges seated passenger	DOT, Deceleration Effects
0.97 deceleration	dislodges sideways-seated passenger	DOT, Deceleration Effects
1.5 acceleration	produces 18% visual errors in reading dials	Gaver
2 acceleration	beginning of subjective feeling of discomfort	Gemmill

Figure 3-1

ACCELERATION MATRIX: LONGITUDINAL ACCELERATION (contd.)

g Force	Effect	Source
3 acceleration	reaction time slows	Gaver
3 acceleration	limit for thigh movement	U. S. Navy
3 acceleration	limit for upward foot movement	U. S. Navy
3 acceleration	extreme limit for effective movement	Air Force Medical Service
4 acceleration	limit for head movement	U. S. Navy
5 acceleration	limit for backward movement of foot	U. S. Navy
6 acceleration	limit for hand movement above head	U. S. Navy
8 acceleration	limit for wrist movement	U. S. Navy
25 acceleration	limit for finger movement	U. S. Navy

Figure 3-1
(contd)

ACCELERATION MATRIX: LATERAL ACCELERATION

g Force	Effect	Source
0.025	passenger perceives acceleration	Dunlop
0.03	passenger begins to be uncomfortable	Dunlop
0.06--0.22	comfortable lateral acceleration for public transit	Gebhard
0.23 and higher	passengers perceive as "too much" lateral acceleration	Gebhard
0.3	knocks over a free-standing person in public transit	UMTA
0.47	knocks over a person holding a fixed rail in public transit	UMTA
2.00	limit for "effective" movement during lateral acceleration	Air Force Medical Service
6.00	most extreme lateral acceleration endurable by unprotected humans	Bergeret

Figure 3-2

ACCELERATION MATRIX: VERTICAL ACCELERATION

g Force (Vertical)	Effect	Source
0.035 at 6.0 to 20.0 Hz	Very good riding comfort despite vertical vibration; at higher and lower frequencies, riding comfort remains good at higher g levels	Hopkins
0.05 at 6.0 to 20.0 Hz	Good riding comfort despite vertical vibration; at higher and lower frequencies, riding comfort remains good at higher g levels	Hopkins
0.07 at 6.0 to 20.0 Hz	Normal riding comfort despite vertical vibration; at higher and lower frequencies, riding comfort remains good at higher g levels	Hopkins
0.10 at 6.0 to 20.0 Hz	Bad riding comfort; vertical vibration produces fatigue and discomfort; at higher and lower frequencies, higher g levels are required to produce this discomfort	Hopkins
0.71 at 4.0 to 63 Hz	Upper limit of vertical vibration tolerable without restraint; exposure times of up to 100 minutes used in producing calculation	Hopkins
15	Maximum shock loading survivable by unprotected shipboard personnel after underwater explosion (short-duration shock)	US NAVSEC

Figure 3-3

ACCELERATION AND THE PRAM SCENARIOS

The PRAM data base includes collision and grounding, swamping, capsizing, and sinking, falls overboard and falls within the boat, and persons struck by the boat or propeller as major accidents types. Since the powering-related problem is defined as a maneuvering-related problem, the accident types involving dynamic instability were examined closely. Scenarios were developed for dynamic instability accidents. In this section of the report, the acceleration matrix data and acceleration boat testing data are related to the dynamic instability scenarios.

Course-keeping

Narrative

Encountering two speedboats going in the opposite direction, an open powerboat is suddenly caught in very choppy wakes. The operator lurches backwards, losing control of the steering, and the boat itself swerves aside from its forward course.

Acceleration Factors

In IDEAMATICS' boat testing, mean vertical accelerations in the ABYC test course were .44 g on the turn, .57 g on the offset, and .59 g on the return. According to the vertical acceleration matrix, 0.71 g at 4.0 to 63 Hz is the upper limit of vertical vibration tolerable without restraint. The vertical accelerations produced by the testing appear quite high. This accident scenario seems to represent extreme vertical accelerations which, added to a steady longitudinal acceleration, cause the driver to lose balance and fall. As the driver stumbles backward, he is then subject to the lateral acceleration resulting from the boat's sideways swerves.

Speed--While Turning

Narrative

A ski-boat operator, noticing that the skier he was pulling has fallen, makes a sharp, high-speed turn in order to return and make a pick-up. The turn is too fast and too sharp, and the boat goes out of control, throwing the persons on board overboard.

Acceleration Factors

The mean lateral accelerations achieved during the ABYC test were .72 g in the turn, .79 g in the offset, and .92 g in the return. The maximum accelerations achieved during the test were 1.75 g in the turn, 4.9 g in the offset, and 2.8 g in the return. According to the lateral acceleration matrix, .47 g knocks over a person holding a fixed rail in public transit. By this measure, all the mean accelerations in the ABYC course would have thrown unsupported POBs overboard. Even more interesting, the Air Force Medical Service states that 2 g is the limit for effective movement during lateral acceleration. It is possible, therefore, for an operator to initiate a sharp turn and generate a g force higher than the limit of effective movement, making it difficult or impossible to initiate corrective action.

Turn--POB Position

Narrative

In the course of an afternoon's outing, a powerboat operator makes a sudden turn to avoid a floating log. The turn coincides with the decision of a passenger to go to the back of the boat to get a towel. The passenger rises from his seat just as the operator initiates the turn, and the passenger is thrown overboard.

Acceleration Factors

Since it is possible, according to ABYC tests, to generate from 0.2 g to nearly 5.0 g of lateral acceleration on a turn, and since, according to the Urban Mass Transit Administration, 0.3 g knocks over a free-standing person in a public transit vehicle (0.47 g knocks over a person holding a fixed rail), it is not surprising that this is a common accident scenario. The fact that the person thrown overboard was already moving contributes to his/her instability.

Turn--Environment

Narrative

A motorboat operator, coming back to shore after a day on the water, while making a turn into the marina channel does not notice the substantial wake of another boat which has just left the channel. The first boat strikes the wake of the second boat with enough force to throw POBs out of the boat and to cause the boat itself to go into a tight spin.

Acceleration Factors

This scenario combines elements of longitudinal, lateral, and vertical acceleration. It is difficult to disentangle the elements sufficiently to discuss each component separately. Generally, what is happening is that the POBs are already experiencing longitudinal and lateral accelerations, possibly quite gentle ones. However, when the wake is struck, relatively heavy vertical accelerations are experienced which interact with the longitudinal and lateral accelerations to unseat the POBs.

RELATIONSHIP BETWEEN ACCELERATION MATRICES AND ABYC TESTS

The test boats were instrumented with accelerometers to measure longitudinal, vertical, and lateral acceleration. Table 3-1, Maximum

Accelerations, following, presents the result of IDEAMATICS' testing for acceleration on the ABYC and turn tests. The number are those of the mean readings (expressed in g's) for each category. Beneath each figure is the range of readings for that category.

	ABYC Test			Turn Tests
	Turn	Offset	Return	
Longitudinal	.135 (.005 - 1.25)	.176 (0 - 1.07)	.125 (0 - .4)	.305 (.002 - 4.3)
Vertical	.442 (0 - 1.75)	.569 (0 - 1.5)	.593 (0 - 1.75)	.894 (0 - 4.7)
Lateral	.722 (.2 - 1.75)	.786 (.09 - 4.9)	.921 (.14 - 2.8)	.742 (0 - 4.3)
Bow	.507 (.5 - .6)			.555 (.05 - 4.2)
Seat	.329 (0 - .7)			

Table 3-1

MAXIMUM ACCELERATIONS

Table 3-2, Matrix/ABYC Test Comparison, on the following page, presents the data from the acceleration matrix depicted with the ABYC test course data.

CONCLUSIONS

The acceleration matrices from the turn tests, ABYC tests and scenario analysis all correlate in that they indicate similar results. The observed accelerations indicate that longitudinal acceleration in boats is not a severe problem. Measured longitudinal accelerations were, for the most part, well within safe ranges according to the baseline matrix data. However, lateral

			ABYC Means
Acceleration	Type	Effect	Turn/Offset/Return
o.3 g	lateral	knocks over free-standing person	.722/.786/.921
0.47 g	lateral	knocks over person holding fixed rail	.722/.786/.921
2.0	lateral	limit for effective movement	.722/.786/.921 (outliers of 4.9 g and 2.8 g were recorded)
0.16 g	longitudinal	unsupported bus standee loses balance	.135/.176/.125
0.23 g	longitudinal	strap-supported standee loses balance	.135/.176/.125
0.27 g	longitudinal	vertical stanchion-supported standee loses balance	.135/.176/.125
0.94 g	longitudinal	dislodges seated passenger	.135/.176/.125 (outliers of 1.25 g and 1.07 g were recorded)
0.10 g (6 to 20 Hz)	vertical	bad riding comfort produced	.442/.569/.593 (no Hz measured)
0.71 g (4 to 63 Hz)	vertical	upper limit of vertical vibration tolerable without restraint	.442/.569/.593 (no Hz measured; outliers of 1.5 g and 1.75 g were recorded)

Table 3-2

MATRIX/ABYC TEST COMPARISON

accelerations in some boats were well above safe ranges, and lateral accelerations featured strongly in most accident scenarios. Vertical accelerations in boats are complicated by the boats' encounters with wakes and chop. The vertical accelerations measured on the ABYC test course were quite high. However, caution must be used in interpreting these data against the matrix data, since many matrix data represented vibration (sustained, high-frequency vertical acceleration) rather than the relatively low frequency vertical accelerations experienced in boats. The primary problem with vertical accelerations is that they combine with other types of acceleration to render unsupported boat passengers unstable and thus lead to falls overboard and within the boat.

CHAPTER IV

REVIEW OF PRAM STUDY

As part of its efforts to develop alternatives to the current safe powering standard, IDEAMATICS closely examined the Powering Related Accident Model (PRAM) data base that was developed during Phase I of this effort. The IDEAMATICS review carefully analyzed the accidents accepted into the data base and provided additional coding designed to supplement the original PRAM data. This process followed four steps: a review of the acceptance of an accident case, an analysis of its acceptability, an expansion of nominally representative engineering data, and a collection of engineering data on the boats involved in PRAM.

The first step included a redefinition of the type of problem being reviewed. There are a number of factors affecting performance and safety under power in addition to the installed horsepower. Even restricting the discussion to the "machine" subsystem (meaning the characteristics of the boat as opposed to the actions of the operator), two boats with the same installed horsepower may react totally differently. The problem is really: what characteristics of the boat make it unsafe or could contribute to an accident when the boat is operated in a prudent and reasonable manner? Therefore, the accidents of interest are more properly "maneuvering-related" accidents than "powering-related" accidents. With this distinction in mind IDEAMATICS analysts reviewed the PRAM data base to select only those accidents, predominently caused by the boat's characteristics, which are maneuvering-related. The review identified 191 accidents out of the 465 accidents in PRAM as acceptable to this definition. The remaining 274 accidents were rejected because their primary causes were reckless operation, operator error, environment, or some other non-applicable factor.

The second step called for an analysis of those 191 accidents to determine which cases fell within the mandate of this effort, i.e., under 20 feet in length, monohulled, and powered by an I/O or an outboard engine. There were 156 "Applicable" cases fitting these requirements. This close screening substantially reduced the size of the data base available for analysis at the same time that it increased the quality and applicability of the information.

The third step was a review of the in-depth accident investigations conducted for the Coast Guard. These accident investigations were used to establish a listing of nominally representative data for possible use in replacing unknowns in the PRAM data.

The fourth step involved searches of the files of the National Marine Manufacturer's Association (formerly BIA). This step led to the positive identification of certain engineering data for specific boats listed in the original Boating Accident Reports (BAR) used in PRAM. In addition, manufacturers of boats were contacted by IDEAMATICS personnel for more information.

Once all the information available had been collected, efforts were made to replace unknown values in the data base by a structured and careful methodology, which is described in the Interim Report. IDEAMATICS analysts then examined the refined PRAM data base for insight into the nature of maneuvering-related accidents.

CHARACTERISTICS OF THE DATA

The analysis of the refined data base requires some preliminary understanding of the nature of the data contained in it.

Data Biases

The file of Boating Accident Reports (BAR) contains certain biases which must be accounted for. Most boating accidents go unreported. The reporting

rate is believed to vary with the severity of the accident, in that cases with little damage are frequently not reported, while fatal accidents are almost always reported. Estimates have been made that as little as 5% of the non-fatal accidents are reported each year, while 95% of the fatal accidents are reported. Economics plays an undeniable part in reporting: damage to a $20,000 powerboat is reported, while damage to a $300 johnboat is not.

Fatality, furthermore, is not an especially reliable indication of accident severity. It does not always correlate with the behavior of the boat. Plenty of people are thrown out of erratically behaving boats and rescued, with no accident report filed, while reports are filed on the deaths (and injuries) of people who die or are injured because they can't swim, or aren't wearing a personal flotation device, or get cramps, swallow water, or are struck by the propeller of a docile and well-behaved boat. The bias of this data base towards "fatal" accidents is further heightened by the fact that the Phase I[i] work used BAR's from 1975 and 1976 to construct PRAM and more particularly, all BAR's from 1975 and only fatal BAR's from 1976. Nonetheless, the BAR's are our data base, the basis of PRAM, and, therefore, the basis of this analysis.

Applicability Criteria

Another point concerning the data base is the criteria used to determine "applicability." Only those accident cases involving boat types subject to the current standard (less than 20' in length, mono-hulled, and propelled by inboard/outboard or outboard engines) were considered "Applicable" to this

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[i] White, R. W., Stiehl, C., Whatley, N., and Blanton, W., A Study to Determine the Need for a Standard Limiting the Horsepower of Recreational Boats, USCG Report No. CGD-36-83, Wyle Laboratories, September, 1978.

study. A total of 156 boats was considered to be "Applicable" and those are the boats contained in this Chapter's analysis.

Through further refinement, those cases of clear operator error or overwhelming environmental situations were eliminated from the data base. It would therefore be expected that collisions (highly related to operator error) and the swamping/capsizing/flooding/sinking (highly related to environment) categories would decrease in relative weight. Those collisions or environmentally-connected accidents that remain are those in which the maneuverability of the boat played an acknowledged role in the causation of the accident.

Data Base Caveats

Two last caveats about this data base exist. The first concerns the question of nomenclature. Boat owners and even manufacturers can be quite casual about designations, whether by trauma, by misinformation, or by the fuzzy nature of the terms themselves. Thus, a boat that a manufacturer might call a "bassboat" may be called a "runabout" or a "fishing boat" by an operator, while the term "bowrider" and "runabout" overlap enormously. The V-shaped hulls offer a similar situation: one man's "deep-V" is another man's "V" and yet another man's "semi-V." Classifications based on terminology are not to be regarded as exclusive or reliable.

The second caveat concerns the nature of the accidents themselves. While the screening and coding exercises performed by IDEAMATICS analysts were designed to eliminate as many non-boat defined influences as possible, it is impossible to remove entirely the effects of operator error, of environmental irregularity, and of sheer contingency. Open powerboats are owned and operated by people with varying levels of experience and seamanship, and with varying acuteness of reflex. A day on the water, with the insidious influences of wave chop, glaring sunlight, and incipient sunburn, can affect the abilities

of the most experienced operators. Weather and water conditions can change suddenly, and many things such as barge wakes or floating logs may remain unperceived until the last moment or until impact. And we can never rule out blind chance: a passenger may stand up to go fetch a towel just at the moment the operator swerves to avoid a tangle of seaweed, while a sudden large wave may hit a ski-boat just as the driver circles to rescue the fallen water-skier. Indeed, the impression received by the reader of the BAR's is that boat configuration and responsiveness are relatively minor contributions to boating accidents, compared with these other factors.

Having offered those disclaimers, we can proceed to an analysis of the 156 PRAM boats and their accidents.

PRAM ACCIDENT ANALYSIS

The first observations to be made about the PRAM cases analyzed are those concerning the physical characteristics of the boats themselves.

Physical Characteristics of PRAM Boats

While the boats ranged from 8' to 18'6" in length, and from 3' to 8' in width (beam amidships), almost three quarters of the boats were from 14' to 16'11" long, and three fifths of the boats with known widths were from 4' to 6'11" wide. Tables 4-1 and 4-2 show the full ranges of those measurements, compared with the boats involved in all accidents reported in CG-357[2] in 1975 and 1976. Table 4-3 shows the distribution of the boats according to hull shape. Discounting the unknowns, by far the most common hull shape (almost two-fifths) was some variant of a "V" bottom. By correlating length with hull shape (Table 4-4), we can achieve a reasonable picture of the set of PRAM boats under analysis.

There are a number of things to note about this set of boats. As far as length is concerned, the large majority of the boats (four-fifths) are between 12' and 17' long. If, however, we look at the lengths broken down according to hull-shape, it becomes clear that three different boat populations

FREQUENCY DISTRIBUTION BY LENGTH

LENGTH	CASES	RELATIVE PERCENTAGE	CG-357 1975-1976
under 12	3	1.9	3.8
12	14	9.0	5.1
13	7	4.5	1.7
14	40	25.6	14.1
15	33	21.2	16.5
16	42	26.9	21.2
17	9	5.8	14.3
18 and over	8	5.1	23.3
TOTAL	156	100.0	100.0

Table 4-1

[2] Boating (Yearly) Statistics, CG-357 (1975 and 1976), United States Coast Guard.

FREQUENCY DISTRIBUTION BY WIDTH

BEAM	CASES	RELATIVE PERCENTAGE	PHASE I PERCENT
0 - 3 FT	4	2.6	2.8
4 FT	34	21.8	12.6
5 FT	29	18.6	15.8
6 FT	32	20.5	20.7
7 FT	17	10.9	13.4
8 FT	1	0.6	8.5
UNKNOWN	39	25.0	21.7
OTHER			4.5
TOTAL	156	100.0	100.0

Table 4-2

FREQUENCY DISTRUBUTION BY HULL SHAPE

HULL SHAPE	CASES	RELATIVE PERCENT
DEEP-V	8	5.1
SEMI-V	26	16.7
V	25	16.0
TRI-HULL	32	20.5
FLAT BOTTOM	30	19.2
OTHER	4	2.0
UNKNOWN	31	19.9
TOTAL	156	100.0

Table 4-3

FREQUENCY DISTRIBUTION BY
LENGTH AND HULL SHAPE

BOAT LENGTH \ HULL SHAPE	V	SEMI-V	DEEP-V	FLAT	TRI-HULL	UNKNOWN	OTHER	TOTAL # OF BOATS
under 12'	0	0	0	3	0	0	0	3
12' - 13'	0	1	2	11	0	0	0	14
13' - 14'	1	2	0	1	2	1	0	7
14' - 15'	7	10	0	12	5	6	0	40
15' - 16'	8	5	1	0	7	12	0	33
16' - 17'	9	2	1	2	15	10	3	42
17' - 18'	0	4	1	0	3	0	1	9
18' and over	0	2	3	1	0	2	0	8
TOTAL	25	26	8	30	32	31	4	156

Table 4-4

are represented here (discounting the thirty-one boats of unknown hull shape). The first population, the flatbottomed boats, tend to be short. Four-fifths are between 12' and 15' long, while only one is over 18'. In striking contrast with these boats are the tri-hulls (also known as cathedral hulls), two-thirds of which are between 15' and 17' long. Indeed, so dense is their concentration at the 16' category that they compose over half of all the boats of that length. There were no tri-hulls under 13'; the longest was 17'2". The third family of boats - the V-hulls - are, as mentioned earlier, the most populous (38%), but also a much more loosely dispersed group. Of them, those designated simply as "V's" are the most tightly bunched: none is over 17' long; only one is under 14'. When it comes to the other two types of V-hull, however, (the semi-V's and the deep-V's), the distribution is looser. Half of the semi-V's are between 14' and 16', but eight are longer, and three are shorter. The deep-V's, few in number to begin with (only eight), show no notable clustering.

From this evidence, one might generalize that the flatbottomed boats involved in the PRAM accidents tend to be under 15', the tri-hulls over 15', and the three V's scattered, with the simple V's and the semi-V's generally in the 14' to 17' range, and the deep-V's sparse in number and of no particular length. (Again, any generalization about the V-family must be tempered by the acknowledgment of the overlapping terminology at work here; many a simple "V" may, in fact, be a semi-V or a deep-V.)

Boat Populations

While we may be tempted to say that shortish flatbottomed boats have accidents, that longish tri-hulls have accidents, and that few deep-V's

have accidents, we cannot make those statements unless we compare this population of PRAM boats with the American boat universe of 1975 and 1976. That flatbottomed boats involved in accidents are shortish probably reflects the fact that most flatbottomed boats are shortish: bassboats, johnboats, fishing boats. Similarly, the fact that the tri-hulls involved in accidents are mostly around 16' may reflect the fact that most tri-hulls manufactured are around 16' long. And, last of all, the fact that only eight out of 156 boats involved in these accidents were designated as deep-V's may not mean that deep-V's are safer boats, but simply that 5% of the recreational open powerboats under 20' long on the waterways of America in 1975 and 1976 were deep-V's. Unfortunately, the segmentation of the Coast Guard's Nationwide Boating Survey of 1976 is too broad to help us here. Its finest calibration tells is that 710 "bowrider runabouts" were under 16', and 1,148 "bowrider runabouts" were between 16' and 25'.

Without a knowledge of the boat universe, then, it is difficult to make generalizations about the boats represented in the PRAM cases. A review of the PRAM accidents reveals that certain brands of boats are involved in several different accidents: there are 5 Starcrafts, 7 Glastrons, 4 Larsons, and 5 Glasspars a division of Larson), involved in as many accidents. Yet we cannot say that Starcrafts or Glastrons or Larsons or Glasspars are unseaworthy boats, because their repeated presence may simply indicate the fact that they are popular, widely-marketed boats.

Length and Hull Shape

A consideration of the boats sorted according to length and hull shape can, however, be useful for this study when the boat parameters are examined in light of various types of accidents. Table 4-5 illustrates how many

FREQUENCY DISTRIBUTION
IDEAMATICS CODED PRAM CASES

ACCEPTED CASES

SECONDARY CAUSE		CASES
ACCEPT, LATERAL ACCELERATION	AS PRIMARY CAUSE	
	COURSE-KEEPING	22
	SPEED-WHILE TURNING	33
	TURN-POB POSITION	20
	TURN-ENVIRON	17
	OTHER, DYN STAB	3
TOTAL		95
ACCEPT, MANEUVERING-COLLISION	AS PRIMARY CAUSE	
	FAILED AVOIDANCE	21
	OTHER, COLLISION	1
PRIMARY TOTAL		22
ACCEPT, ENVIRONMENT	AS PRIMARY CAUSE	
	COMBINED SPEED AND WEATHER	3
	COMBINED SPEED AND LOCATION	3
	OTHER, ACCEPT ENVIRON	10
TOTAL		16
ACCEPT, VELOCITY CHANGE	AS PRIMARY CAUSE	
	START-IN-GEAR	10
	SUDDEN SURGE	8
	OTHER, VEL CHANGE	2
TOTAL		20
ACCEPT, OTHER	AS PRIMARY CAUSE	
	ACCEPT, OTHER	3
TOTAL		3
ACCEPT TOTAL		156

Table 4-5

boats were involved in the various accident categories, and Table 4-6 shows the 156 boats arranged according to length and hull shape within those accident categories. Explanation of accident types is contained in Table 4-7. Examination of Tables 4-5 and 4-6 shows us that the category of lateral acceleration contains by far the greatest number of cases with the three accident types associated with turning--too much speed in a turn; POB position during a turn; adverse environmental factors encountered during a turn--representing 44.9% of all the cases. Considering the distribution in light of hull shape, it is interesting to note that a very large proportion of the flatbottomed boats were involved in lateral-acceleration accidents (75%). No flatbottoms were involved in maneuvering-collision accidents, while one was in an environmentally influenced accident, and the remainder in velocity-change accidents. The tri-hulls, likewise, were overwhelmingly involved in lateral acceleration accidents (80%). Of the remaining tri-hulls, three were in failed-avoidance accidents, and three in environmentally-influenced accidents, with none involved in velocity-change accidents. In comparison with the flatbottoms and tri-hulls, and their heavy representation in course-keeping/turning problems, the deep-V boats were sparsely represented in this type of accident: there were only two deep-V boats involved in collision (failed avoidance) accidents (although it is perhaps misleading to speak of a "great number" when it means four boats and the total number of deep-V's is only eight). As for the remaining members of the V family, half of the simple V's were in lateral acceleration accidents, and the remainder equally distributed between the two remaining categories. The semi-V's showed a somewhat more pronounced concentration within the lateral acceleration category (69%), the remaining cases being more or less evenly scattered among the other categories. Curiously, all of the boats

LATERAL ACCELERATION ACCIDENTS

	V	Semi-V	Deep-V	Flat	Tri-Hull	Unknown	Other
under 12		1		2			
12'-13'			1	9			
13'-14'		2		1	2	1	
14'-15'	3	8		9	4	5	
15'-16'	4	4			6	3	
16'-17'	5		1		12	6	
17'-18'		2			1		
18'& over		1			1	1	
Total	12	18	2	21	26	16	

FAILED AVOIDANCE

	V	Semi-V	Deep-V	Flat	Tri-Hull	Unknown	Other
under 12'			1				
12'-13'							
13'-14'							
14'-15'	2				1	1	
15'-16'	1						
16'-17'	3	2	1		1	1	3
17'-18'			1		1		1
18'& over			1			1	
TOTAL	6	2	4	0	3	3	4

Table 4-6

ENVIRONMENTALLY INDUCED ACCIDENTS

	V	Semi-V	Deep-V	Flat	Tri-Hull	Unknown	Other
under 12'				1			
12'-13'						1	
13'-14'			1				
14'-15'	2						
15'-16'	1	1			2	4	
16'-17'							
17'-18'		1			1		
18'& over		1					
TOTAL	3	3	1	1	3	5	

VELOCITY CHANGE ACCIDENTS

	V	Semi-V	Deep-V	Flat	Tri-Hull	Unknown	Other
under 12'							
12'-13'				2			
13'-14'	1						
14'-15'		2		3		1	
15'-16'	1		1			3	
16'-17'	1			1		2	
17'-18'		1					
18'& over			1				
TOTAL	3	3	2	6	0	6	

Table 4-6 (contd.)

ACCIDENT CATEGORIES

I. Primary cause: Lateral Acceleration. The boat is not steady as it goes. It exhibits dynamic instability.

A. Course-keeping. When the operator relinquishes control, the boat swerves aside from its forward course.

B. Speed While Turning. As operator initiates a high-speed turn, and the boat goes out of control.

C. Turn -- POB Position. An operator makes a sudden turn. A passenger in a precarious position (rising, sitting on the rail) is thrown overboard as a result of the sudden instability.

D. Turn -- Environment. An unnoticed hazard causes the boat to turn sharply.

E. Other. Related to dynamic instability but not fitting exactly into the other categories.

II. Primary cause: Maneuvering -- Collision. An accident occurs which is related to collision avoidance actions of the operator.

A. Failed Avoidance. Collision threat and occurrence happen too quickly for the operator to respond adequately.

B. Other.

III. Primary Cause: Environmentally-Influenced.

A. Combined Speed and Weather. A boat is not seaworthy at a certain speed under certain wind and water conditions.

B. Combined Speed and Location. A boat cannot be maneuvered quickly enough in a restricted location.

C. Other.

IV. Primary Cause: Velocity Change. A sudden surge of power indicates the accident.

A. Start-in-Gear. A boat, started while it is in gear, jolts forward suddenly.

B. Sudden Surge. Through operator inadvertance on mechanical mishap, the boat suddenly aurges forward.

C. Other.

V. All other acceptable cases.

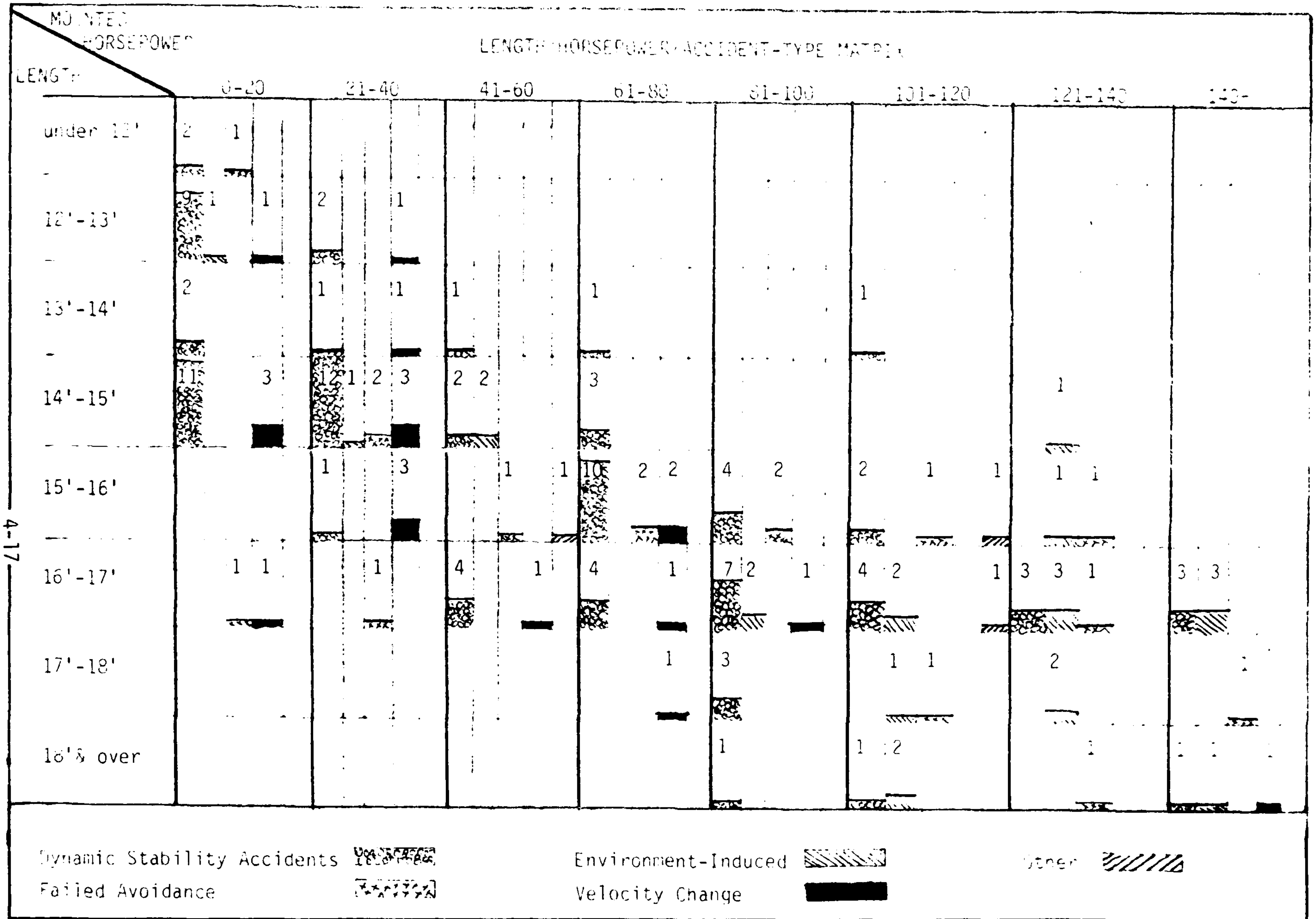
Table 4-7

classed as "other"--tri-marans, a pad-hull, a "tri-V"--are all longer boats (over 16') and all involved in maneuvering-collision accidents.

As far as length is concerned, we may note that the great majority of boats involved in lateral-acceleration accidents were under 17' long (94%). Among the longer boats (17' and longer), 6 were in lateral-acceleration accidents, 5 in maneuvering-collision accidents, and 3 and 2 in environmentally-influenced and velocity-change accidents respectively. Of the shorter boats (under 14') 19 were in lateral acceleration accidents, 1 in a collision accident, 3 in environmentally-influenced accidents, and 3 in velocity-change accidents. The shorter boats, then, were clearly proportionately much more heavily involved in lateral acceleration accidents than the longer boats. Of the mid-length boats (14' to 17'), the majority, as expected, were in lateral acceleration accidents (63%). The distribution of the remaining 41 boats, however, offers some surprises, in that, of the sixteen 14' - 17' boats involved in maneuvering-collision accidents, 11 were 16' to 17' long. Eight of the ten mid-range boats involved in environmentally-influenced accidents, on the other hand, were 15' to 16' long. The 15 mid-range boats involved in velocity-change accidents were evenly distributed.

Length and Horsepower

Table 4-8 shows the FRAM boats arranged according to length and horsepower, and further classified according to the four major accident types. Examination of this matrix reveals that accidents occurring as a result of lateral acceleration and environmental influences seem to be fairly evenly distributed. That is, they may happen to all boats regardless of size and horsepower, with a little thinning of the lateral acceleration accidents towards the top of the scale. The matrix reveals that the other two accidents, however--velocity change and failed avoidance--tend to restrict themselves to either end of the length/power scale. Velocity change accidents seem to occur with



LENGTH-HORSEPOWER-ACCIDENT-TYPE MATRIX
MOUNTED HORSEPOWER
LENGTH
0-20
21-40
41-60
61-80
81-100
101-120
121-140
140-
under 12'
12'-13'
13'-14'
14'-15'
15'-16'
16'-17'
17'-18'
18'& over
Dynamic Stability Accidents
Failed Avoidance
Environment-Induced
Velocity Change
Other

Table 4-8

greatest frequency to shorter, lower powered boats. Failed avoidance accidents, on the other hand, seem to occur with greatest frequency to longer, higher powered boats.

Conclusions

To summarize the findings of our examination of these Tables, then, we may observe that flatbottom and tri-hulls under 17' are disproportionately likely to be involved in lateral acceleration accidents. Longer boats and deep-V boats, on the other hand, are more equally involved in all four kinds of accidents. Shorter, lower powered boats suffer more velocity-change accidents, while longer, more powerful boats suffer more failed-avoidance accidents. If, however, we are to put these conclusions to good use in the reduction of accidents, it will be necessary to restate our observation of the dangerous behaviors of the 156 boats in a more quantifiable form. In other words, one must determine what physical forces are at work within the boat when POB's are thrown out of boats or thrown to the deck as a result of oversharp or overfast turns, or sudden forward surges. We must determine what happens when an operator cannot maneuver a boat well enough to avoid a collision or to compensate for adverse physical conditions.

Boat Physical Actions

The physical actions of a boat may be divided into four categories: stability, maneuverability, cyclic manifestations, and kinematics. The first two categories include boat behavior associated with the relationship of driver and boat: course-keeping (straight and turning), turn responsiveness, turn radius. The third category - cyclic manifestations - comprise aberrant repetitive behavior a boat can exhibit, such as porpoising or chine-walking. The fourth category - kinematics - includes ways of describing

the boat's shifting relationship to its central axes (pitch, roll, yaw), and, most importantly for the passengers of a boat, the kinds of acceleration to which POB's will be subjected within a boat. In a certain sense, however, when it comes to the harm of human beings, many of these types of behavior may be expressed in terms of acceleration. It is, indeed, acceleration-- longitudinal, vertical, lateral-- which throws passengers and operators out of a boat, or to the deck, or into equipment or fellow riders, or away from controls. To be sure, acceleration is not a major factor in determining whether an operator will be able to maneuver a boat fast enough to avoid a fallen skier, or a suddenly sighted wake or floating object, but, the moment that operator acts to avoid collision, he will dramatically change the acceleration forces within his boat. Lateral acceleration is perhaps the most potentially dangerous acceleration. Indeed, the three turning-related accident types found in PRAM represented 44.9% of all the cases. But we cannot totally discount longitudinal and vertical accelerations. Sudden longitudinal accelerations have their risks, as the twenty PRAM accidents included in the velocity-change accident category attest. Injuries and damages inflicted in these accidents are almost exclusively the result of harsh longitudinal acceleration. Vertical acceleration, while not so strongly tied to any one accident category, is no less dangerous. Its potential for harm lies in the fact that it can combine with and intensify the other accelerations. Thus we must recognize that a lateral acceleration strong enough to cause notice but not strong enough to throw a POB out of the boat can become dangerous if it is combined with vertical acceleration. That is, a passenger who has lost complete contact with his seat (as a result of vertical acceleration) is much more subject to longitudinal and lateral forces once his own counter-balancing downward 1g is reduced.

Measuring Physical Forces

While an actual accident may only be described, acceleration forces may be measured, as may many of the other kinematic, cyclic, maneuvering, and stability factors. IDEAMATICS' boat testing program was designed to measure these various factors, and Table 4-9 enumerates the factors, the means of measuring them, and the tolerance for each. The next chapter of this report describes the test program and the data developed from it. The physical forces measured on the test boats are approximations of the forces at work in the PRAM accidents. The dynamic-stability accidents, for instance, occurred as a result of defective course-keeping and turn-responsiveness factors; the three turn-related accident types clearly exhibit high lateral and perhaps also vertical accelerations. The maneuvering-collision accidents, while clearly more oriented toward course-keeping and responsiveness factors, may also be complicated by lateral (and vertical) accelerations, as are the environment-influenced accidents. Factors involved in velocity-change accidents are primarily longitudinal accelerations and course-keeping factors. With all these accident types, however, we must bear in mind the fact that directional acceleration is always a factor. "Maneuverability" means ability to turn, and turning means lateral acceleration. Equally, course-keeping ability, once lost, means a turning or even spinning boat and, concomitantly, lateral accelerations. The activities of the testing program will, then, recapitulate the forces active in the PRAM accidents. Naturally, no testing program can actually replicate what happened in all of the accidents, or even replicate what happens in a typical accident. Parallels cannot be exactly determined. For one thing, the PRAM boats were, in the aggregate, shorter, lighter, and of a lower horsepower than the test boats. But a testing program can measure a great many of the physical factors involved in boat operation and, using those measurements, we can construct models with which to predict boat activity.

POWERING ANALYSIS COMPONENTS

Factor	Measure	Tolerance
Kinematics		
Lateral acceleration	lateral accelerometer	corollary research
Vertical acceleration	vertical accelerometer	corollary research
Longitudinal acceleration	longitudinal accelerometer	corollary research
Offset forces	bow accelerometer	corollary research
Pitch	artificial horizon	--
Roll	artificial horizon	--
Yaw	turnbank indicator	--
Cyclic		
Porpoising	observation	corollary research
Chine walking	observation	corollary research
Maneuverability		
Turn Responsiveness	ABYC Avoidance Course Zig Zag Course	pass/fail t.b.d.
Turn Radius	Quick Turn Test Turn Radius Course	t.b.d. t.b.d.
Stability		
Driver Reaction	observation	pass/fail
Course Keeping, Turning	Quick Turn Test	pass/fail
Course Keeping, Straight	Jerk Test	pass/fail
Other Failure	observation	pass/fail

Table 4-9

CHAPTER V

TEST PROGRAM DESCRIPTION AND ANALYSIS

In fulfillment of Task 6 of the safe powering project, IDEAMATICS developed and executed a recreational powerboat testing program. The goal of the testing program was to obtain data that would assist both in defining the powering problem and in identifying the best solutions. As reported previously, there exists a paucity of data which define exactly how small boats turn and even fewer data which firmly establish the relationship between a specific characteristic of a boat (for example, transom width) and maneuverability. Thus, in order to propose potential solutions to maneuvering accidents, it was essential to learn more about the manner in which boats move. Of equal importance with understanding how a boat maneuvers was identifying critical boat characteristics which had the potential to be useful in predicting maneuverability or which could be used to affect controlability. Thus, defining the problem and identifying solutions were the primary purposes of the testing. When, in addition to these dual purposes, the number of variables in the boats within the scope of the project are considered, the task of selecting appropriate tests becomes complex.

The selected tests are a mixture of standard, industry-used maneuverability tests and project-unique tests designed to test certain potential solutions. In the former category are the ABYC Avoidance Test and the ABYC Quick Turn Test. In the latter are the Zig Zag Test and Wake Hop Test. In all, seven different tests were run. Each test is described below.

STRAIGHT COURSE

This test consisted of several runs through a straight course. The test was used both to calibrate the speed versus RPM curve of the boat/

engine combination and to observe and record certain phenomena such as planing and porpoising. These tests were run at each of three trim settings: trim for maximum speed, average trim, and trimmed fully under.

The tests were run alongside the ABYC Avoidance course. In this way, the course buoys were used to assist the test-boat driver in steering a straight course. The chase boat, with a radar gun, was positioned at either end of the course in order to obtain a head-on reading of the test boat's speed (see Figure 5-1). Personnel in the chase boat observed and recorded the speed at which planing occurred and determined the frequency of any porpoising by counting the number of pitch cycles occurring during a fifteen second interval.

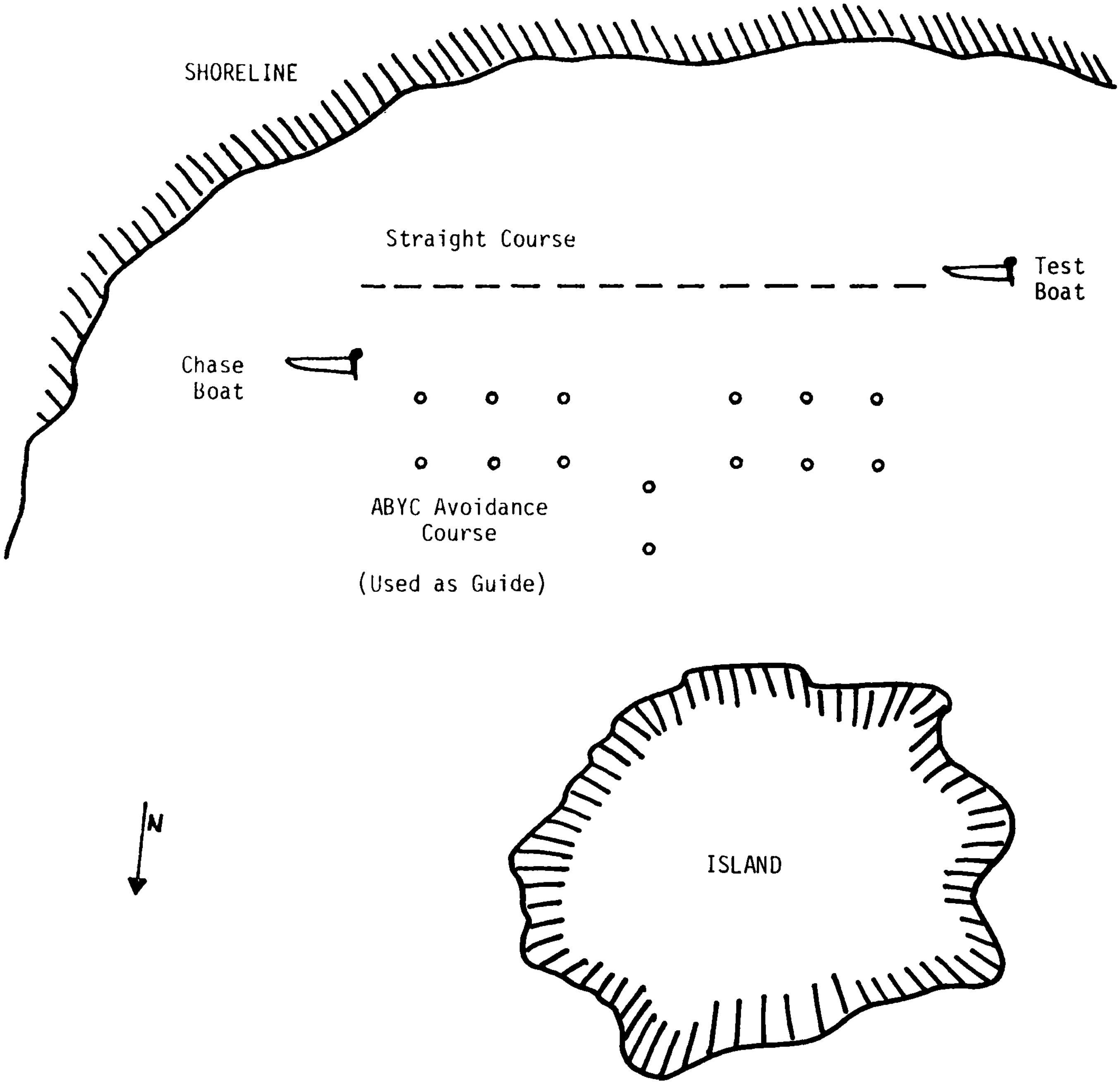
At least three runs were made for each trim setting. These runs were made at full, three-quarter, and one-half throttle.

ROLL/YAW OSCILLATION

This test was designed to measure the boat's susceptibility to roll/yaw oscillation. This test was run along the straight course. While in that course, the test-boat driver input a small-amplitude, transient displacement to the steering system in one direction and then, after judging the reaction of the boat, input a similar displacement in the opposite direction. The result of the test was the subjective judgment of the driver who gauged the reaction of the boat to the perturbation (i.e., whether the boat starts "hunting" or oscillating in roll and yaw).

TURN RADIUS

This test was run through a set of measuring buoys to determine the turn radius and maneuvering capability of the boat. A four-quadrant course



STRAIGHT-ON COURSE

Figure 5-1

was established by placing two rows of buoys at right angles. Each row contained buoys spaced at twenty-foot intervals to be used as measurement markers. The chase boat was positioned so as to avoid collision with the test boat while measuring both the entrance and exit speed of the boat in the course (see Figure 5-2).

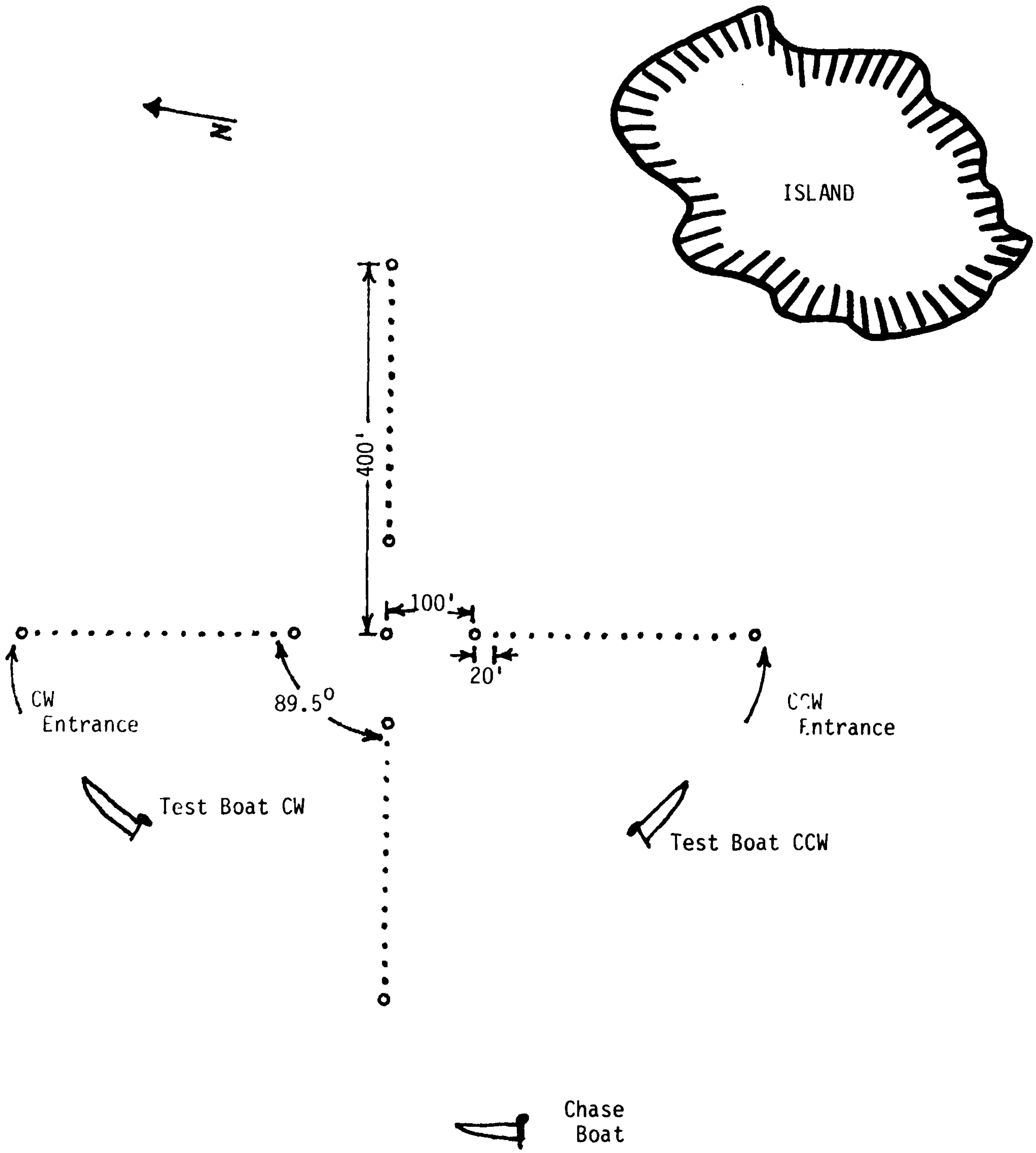
The test-boat driver brought the boat up to the maximum RPM and steered a course at a right angle to the first set of buoys. Upon reaching the first set of buoys (course entrance), the driver quickly turned the helm a specified amount and held the rudder until the boat had turned at least 360 degrees. The chase boat personnel measured the entry speed and exit speed (after the 360 turn) and observed where the boat crossed the measuring lines of the course.

At least three runs were executed in each direction, clockwise and counter clockwise. These runs used helm changes of one-quarter, one-half, and three-quarter turns.

ZIG ZAG

This test was designed to collect specific turn data on the maneuvering capability of the test boat. Its basic purpose was to measure responsiveness to helm changes. The test was run in open water and was composed of a series of turns to predetermined headings.

The test started with the test-boat operator accelerating to maximum RPM and steering a straight course. Once the boat reached steady state, the driver quickly applied a one-half turn to the right until the original heading had changed by 45 degrees. At that point, the driver quickly turned the helm to a one-half left turn and held that turn until the



TURN RADIUS COURSE

Figure 5-2

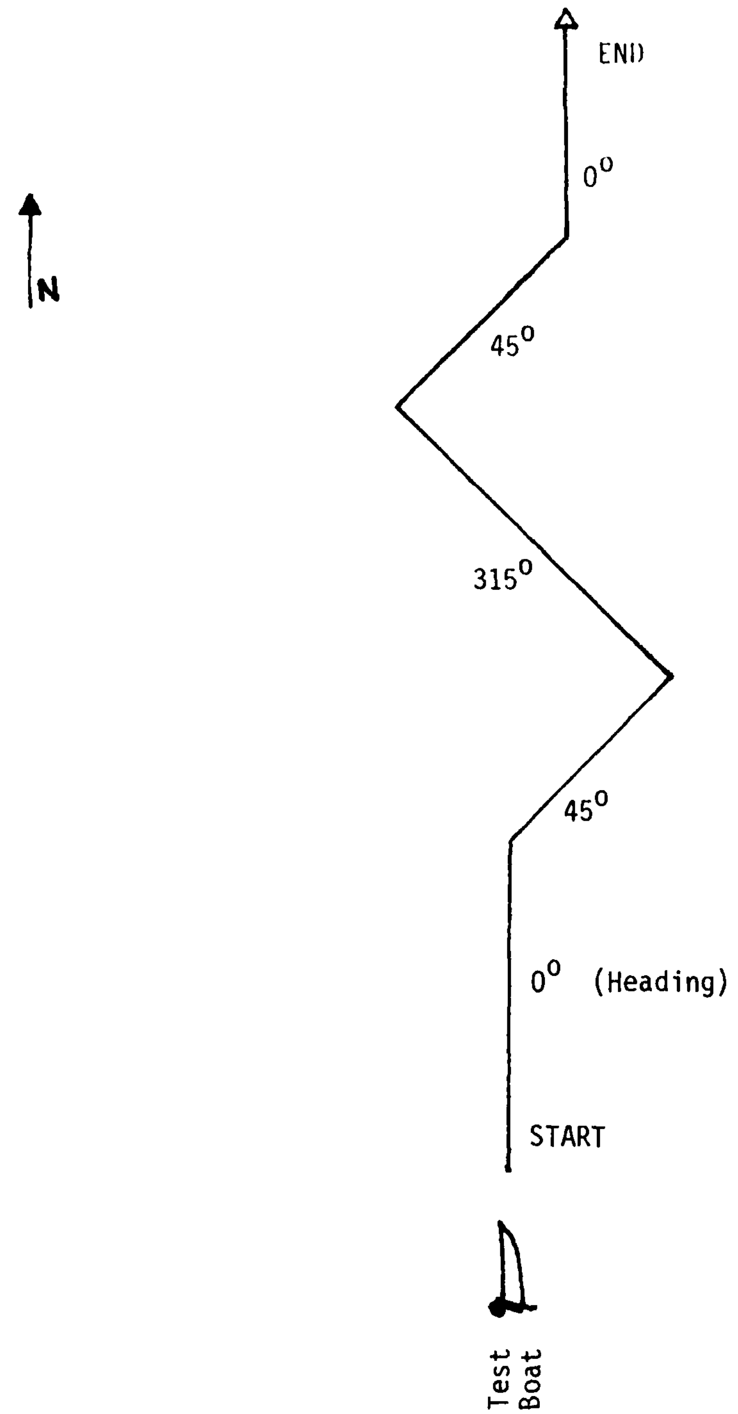
boat came to a heading 45 degrees to the left of the original heading. Again, the driver quickly turned the helm to the one-half right turn position and held the turn until the boat's heading was 45 degrees to the right of the original course. During this test all data are collected automatically by the instrumentation. Figure 5-3 depicts a typical Zig Zag run.

ABYC AVOIDANCE COURSE

This test is taken from ABYC H-26.7.d and provides a measure of the boat's ability to maneuver and avoid obstacles. Figure 5-4 depicts the course. The test-boat driver brought the boat up to maximum speed and ran the course, passing outside the designated avoidance marker without contacting any of the course markers. If the boat could not negotiate the course, the test was repeated at successively lower speeds until the boat stayed within the markers. The test is run for both port and starboard turns. The chase boat was positioned off the end of the course to measure the speeds at which the boat exited the course and to judge whether the run was successfully made. (It should be noted that the avoidance marker varies in distance from the course depending upon the boat's speed.)

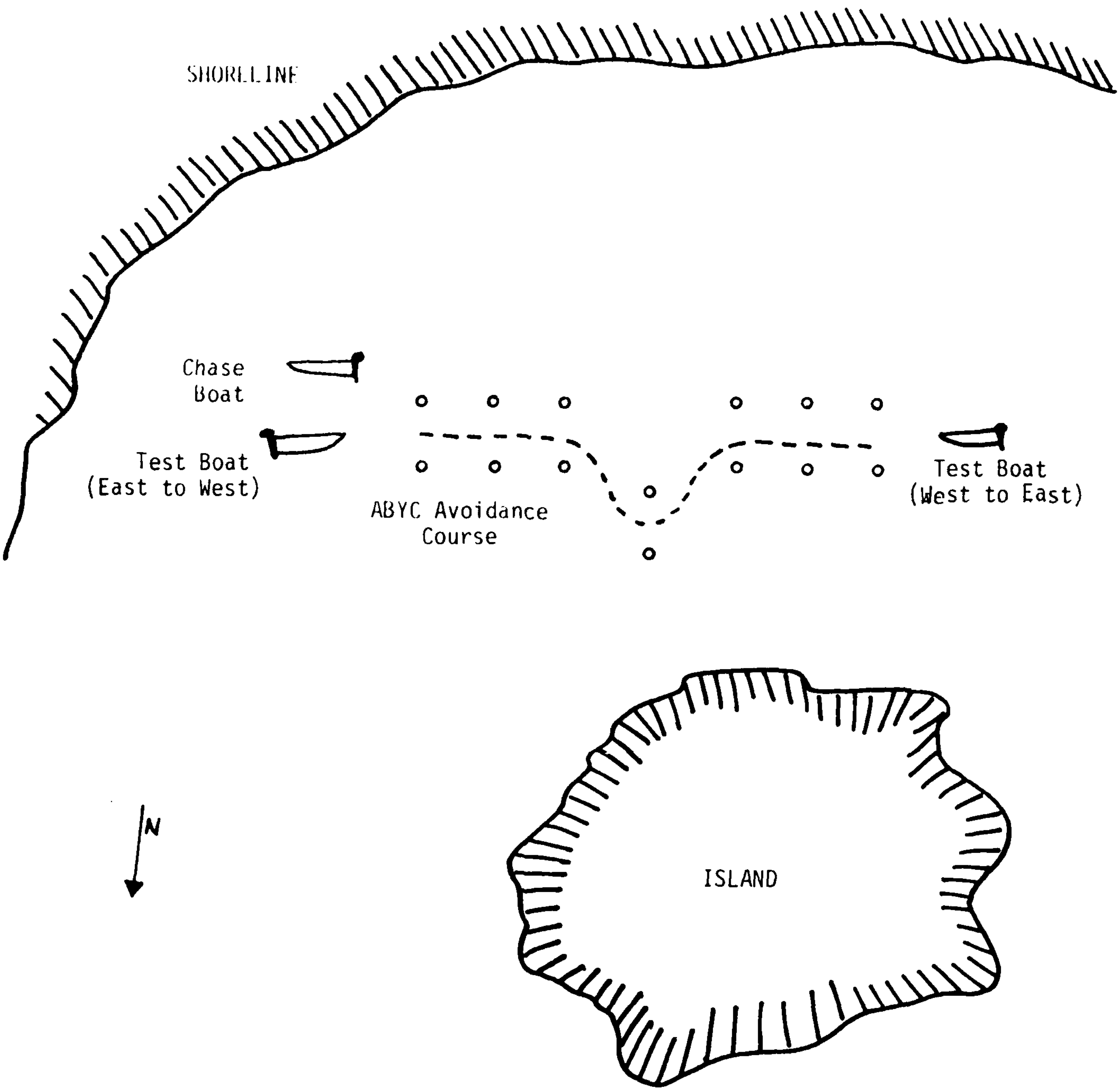
ABYC QUICK TURN

This test is taken from ABYC H-26.7.c and is designed to determine the maximum stable maneuvering speed of the boat. The boat was run through the Turn Radius course described above. The boat was run at the maximum speed and a quick half-turn of the helm was executed upon reaching the first set of buoys. If the boat completed the turn without endangering the driver, the maneuvering speed was the maximum speed. If the turn was not so completed, the speed was lowered until the run could be suc-



ZIG ZAG COURSE

Figure 5-3



ABYC AVOIDANCE COURSE

Figure 5-4

cessfully completed. Testing started at maximum speed and worked down. These runs were made with turns in both directions, left and right.

WAKE HOP

Several of the boats also ran through a Wake Hop test to determine the boat's reaction to high waves or the wake of another boat. In this test the chase boat would generate the largest wake possible and the test boat would pass through the wake at a right angle to the wave's velocity. All measurements were done automatically by the instrumentation.

TEST BOATS AND ENGINES

For these tests, the U.S. Coast Guard provided the set of boats and engines listed in Tables 5-1 and 5-2. Each boat was run through the set of tests with the engine most nearly matching its rated horsepower. In addition, most of the boats were also run through the tests with a second engine, usually the next higher powered. Finally, most of the boat/engine combinations were run through the test set twice in order to obtain a gauge on test repeatability and validity.

TEST INSTRUMENTATION

In order to document the conduct and results of the tests, five types of measuring and recording mechanisms were utilized: magnetic tape recording of data, 8 mm film camera, magnetic tape recording of test boat driver comments, manual recording of observed events, and videotape. These recording mechanisms were utilized with the various measuring devices to collect a wide range of test data at a reasonable cost. Each of the

TEST BOATS

Manufacturer	Model
Angler	V17F O/B
Bonito	5 CBR Tri-Hull
Dolphin	Super-Dolphin O/B
Hawaiian	17' I/O
Higginbotham	174 O/B
Hydra-Sports	Ski, 17'3" O/B
Laminated	12' Bass Boat
Nuco	19' Caribe I/O
Sears	Aluminum Jonboat
Seminole	14' Shallow Hull O/B
Sportsman	13' Fallow O/B
Sterling	T17 Tunnel O/B

Table 5-1

TEST ENGINES

Manufacturer	Horsepower
Outboard Motors:	
Evinrude	115
Evinrude	75
Evinrude	55
Evinrude	25
Evinrude	15
Mercury	200
Mercury	150
Johnson	235
Outboard Motor	9.9
Johnson	7.5
Inboard Motors:	
Outboard Motor Co. (Hawaiian)	140
Mercruiser (Neico/Caribe)	198

Table 5-2

recording mechanisms and its associated measuring instruments is discussed below.

MAGNETIC TAPE RECORDER

The magnetic tape recorder gathered the data from the electronic instruments and stored it on a multi-channel magnetic tape. During the testing, six channels were used to record simultaneously the accelerations experienced along the three orthogonal axes at the center of gravity, the acceleration in the vertical direction at the bow of the boat, the force felt in the driver's seat, and the comments of the test boat driver. The recorder used was a Hewlett Packard Model 3968A.

The accelerations were measured using Endevco Model 2262-25 accelerometers. Three of the accelerometers were mounted orthogonally on an aluminum block. The block was then clamped to a pole so that the accelerometers sat at the center of gravity (c.g.) of the boat. The fourth accelerometer was mounted in the bow of the boat and was oriented to measure in the vertical direction. Photo V-1 shows the pole onto which the c.g. accelerometer package was strapped. (The package is at the bottom of the pole.) Photo V-2 shows the placement of the bow accelerometer (forward of the movie camera in the bow of the Angler).

A seat pad displacement transducer measured the acceleration experienced by the driver in a seated position. This transducer, Endevco Model VT-1, was strapped to the driver's seat and connected to the recorder via the signal conditioners. The seat pad transducer can be seen in Photo V-1.

In order to eliminate high frequency noise from the signals coming from the accelerometers, the accelerometers were connected to Endevco Model 4423 signal conditioners. These instruments served as both conditioners

Center of Gravity Pole and Seat Pad

Photograph V-1

Bow Accelerometer

Photograph V-2

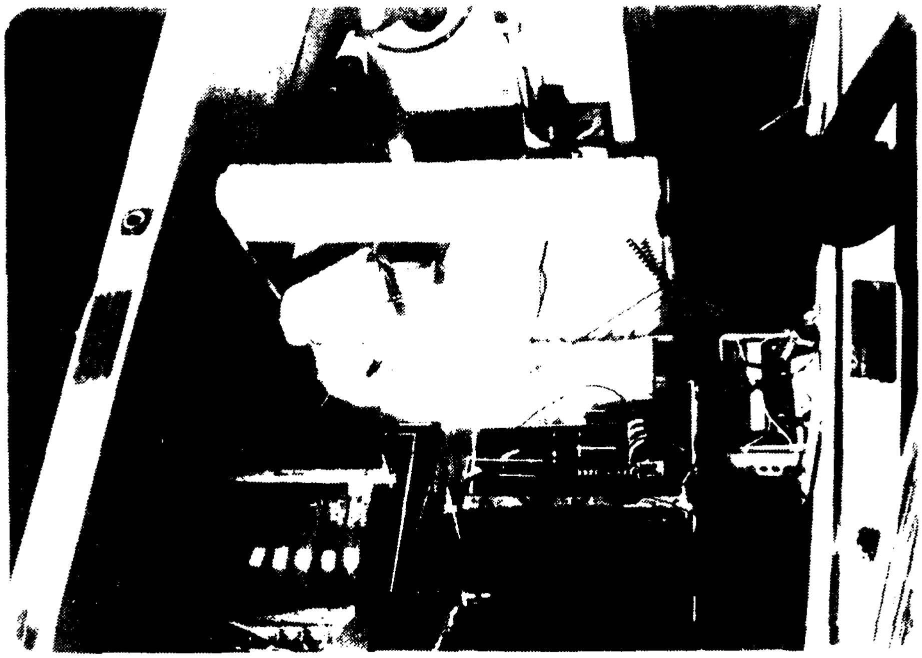
and bridge amplifiers which presented a sufficiently strong and clear signal to the recorder. Photo V-3 depicts the five signal conditioners in the lower left of the picture.

Finally, the magnetic tape recorder is used to record the comments of the test boat driver during the test. These comments are later used to synchronize the recorded data to known events or to the film.

8 MM FILM CAMERA

The second group of data centers about the 8 mm movie camera which was operated during certain tests. This camera was used to record the measurements of a group of aircraft instruments mounted in the boat. Depending upon the test, the camera was operated at a speed varying from one frame every two seconds to eighteen frames per second (normal speed). The instruments recorded by the camera included:

Instrument	Usage
Aircraft Artificial Horizon (Barfield Instruments Model 5000 B)	Display pitch and roll
Aircraft Directional Gyro (Barfield Instruments Model 4000 B)	Display compass heading and provide reference for pitch, roll and skid measurements
Aircraft Bank and Turn Gyro (Barfield Instruments P/N 1234T100-ST)	Display skid
Aircraft 8-day Clock (Barfield Instruments)	Display time reference
Turn Angle Indicator (Custom made by U.L.)	Display motor turn angle
Active Test Indicator (Custom made by U.L.)	Indicate test in progress



Signal Conditioners and Magnetic Tape Recorder

Photograph V-3

Photo V-4 shows the set of instruments mounted in their aluminum frame and the camera aimed at the instrument package. In front of the instrument package is the vacuum pump (Grainger P/N 2Z628) which provided the vacuum required by the gyro instruments.

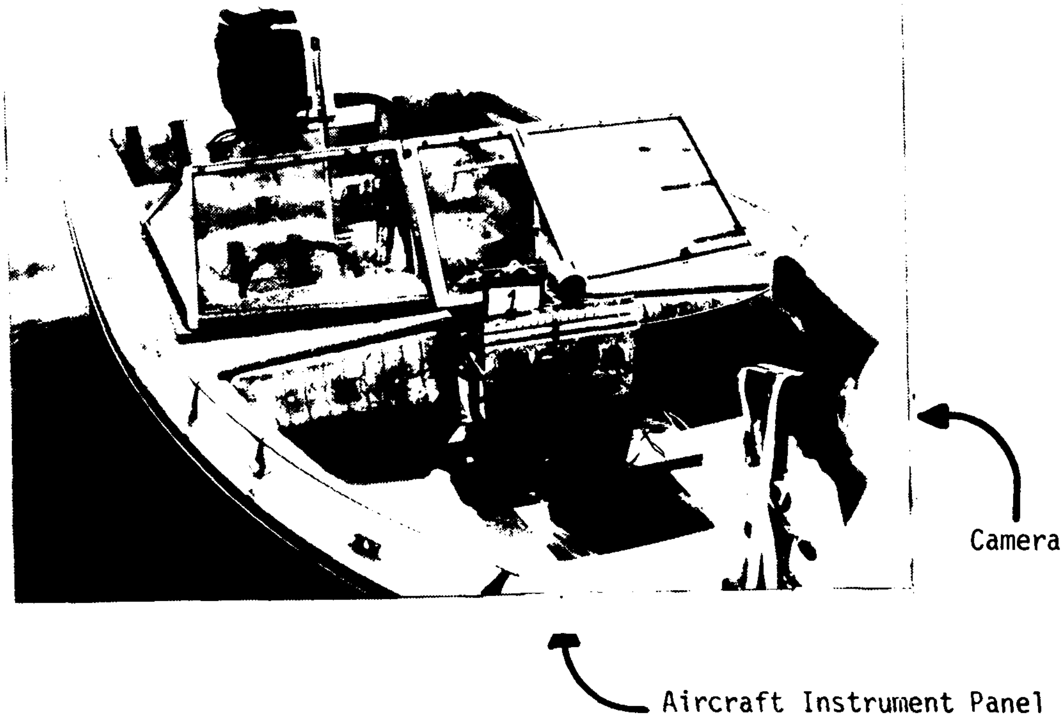
MANUAL RECORDING

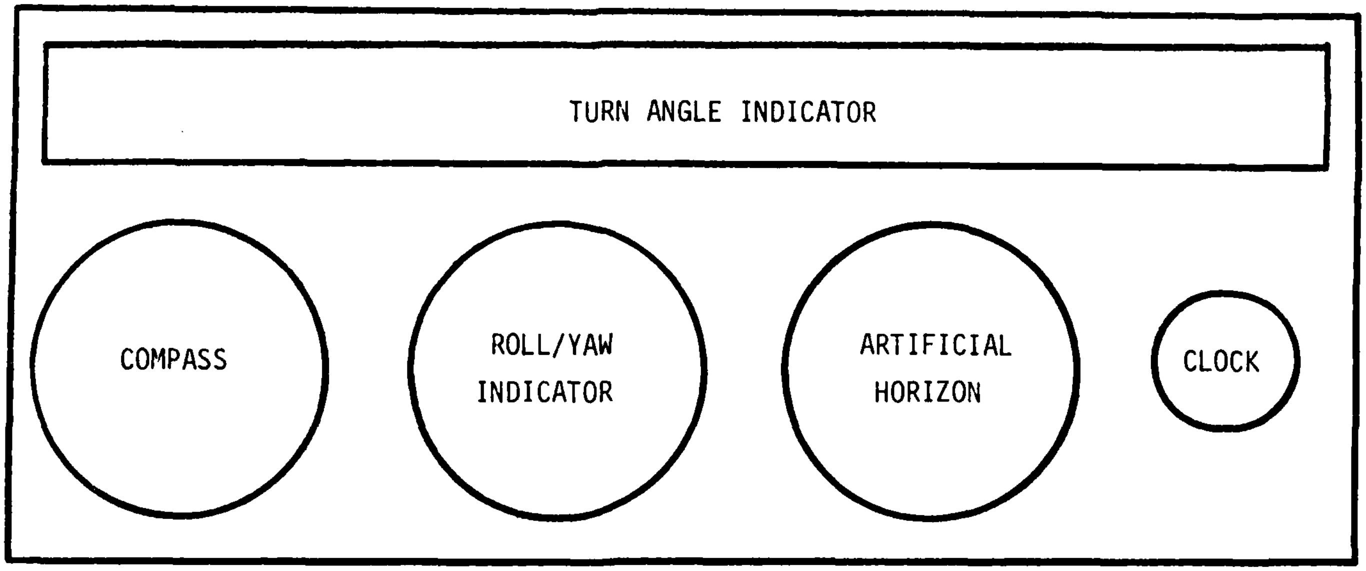
For some of the tests, test personnel observed or measured certain events. For example, during the straight course runs, chase boat personnel measured the speed of the test boat using a hand-held radar gun (Kustom Electronics Model HR-8) and counted the frequency of pitch cycles during porpoising. In all the tests in which test boat personnel measured or observed the tests, data sheets were completed.

DATA REDUCTION

After testing was completed, the data from the films, recordings, tapes, and strip charts had to be transcribed into useable form. The process for the films involved two steps. First, the films were reviewed and a film inventory was made, which catalogued each boat name, run number, test type, and test number contained per film. Next, the films were viewed, run by run, test by test, and the data from three tests--the quick turn tests, the turn radius tests, and the zig zag tests--were transcribed. That is, timings were done, compass bearings recorded, and other relevant data such as turn angles were ascertained. Each test was timed three times to assure accuracy. The last step of this transcription was to standardize the timings, that is, to account for the different speeds of filming and of projecting the film.

Comments of the test-boat driver captured on the tape recorder were copied onto the strip charts, and the strip charts were, in turn, examined to ascertain





AIRCRAFT INSTRUMENT PANEL

maximum and steady state readings for the relevant tests. These readings were then translated into g's.

Following these operations, all data were entered into the appropriate standardized report forms.

TEST REPORT FORMS

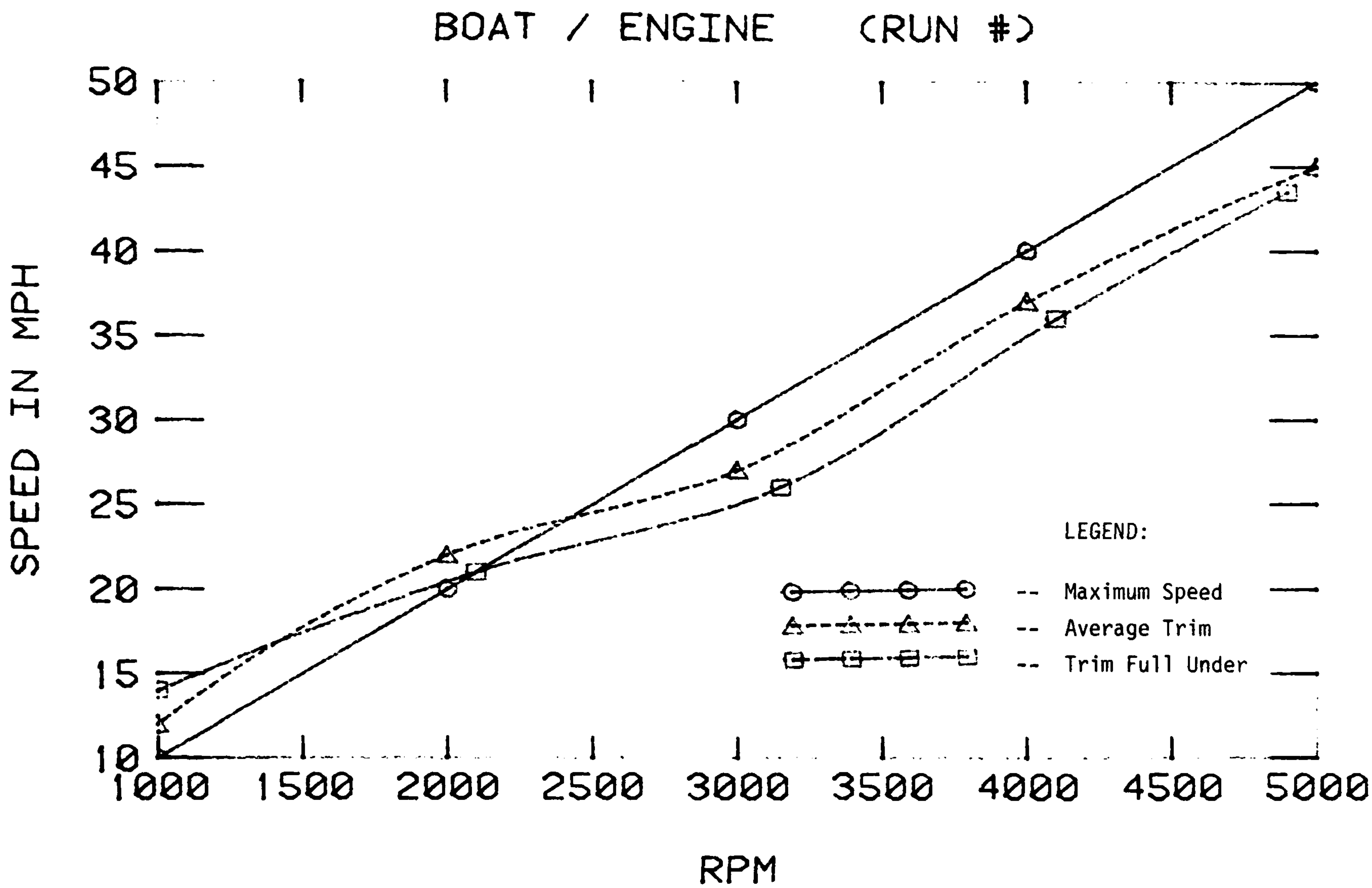
The test results are given in a set of nine forms, as follows:

1. Boat photographs
2. Land Data sheets
3. Speed vs. RPM curves
4. Speed vs. RPM Test report
5. ABYC Avoidance Course report
6. ABYC Avoidance Course (Accelerometer Data) report
7. Turn Radius/Quick Turn Tests report
8. Turn Radius/Quick Turn Test (Quadrant Citings) report
9. Zig Zag Test report

The Boat photographs and Land Data sheets are self-explanatory. Whenever possible, photographs have been included to depict the boat from the bow, beam and stern. In addition, the beam view shows the location of the center of gravity with a black tape crosshair. The remainder of the report forms are explained below.

Speed vs. RPM Curves

These curves show the relationship between velocity and engine RPM for the given boat/engine combination. The data were obtained during the straight course tests and are reported tabularly in the next described report. Figure 5-5 shows a sample graph. At the top of the graph is the boat and engine for which the data apply and the run number during which the data were taken. All graphs show three curves, representing the three trim angles which were tested: maximum speed trim, average trim, trimmed fully under. Maximum speed trim is plotted using circles to show the data points and a solid line to connect the points. Average trim uses triangles and a short-dashed line.



BOAT / ENGINE (RUN #)
SPEED IN MPH
50
45
40
35
30
25
20
15
10
1000
1500
2000
2500
3000
3500
4000
4500
5000
RPM
LEGEND:
-- Maximum Speed
-- Average Trim
-- Trim Full Under

Figure 5-5

Under trim is shown as rectangles joined by a longer-dashed line. The lines which connect the data points are computer-generated by a splining technique.

Speed vs. RPM Test Report

This report form details the straight course tests. These tests were run at three motor trim angles and were run at approximately full throttle, 3/4 throttle, 1/2 throttle, and planing. Figure 5-6 shows a sample of the form with circled letters to key the explanation below.

- A - Specifies the motor trim at which the tests were conducted.
- B - Specifies the angle, in degrees, between the shaft of the motor and the local vertical for the given trim.
- C - Specifies the angle, in degrees, between the transom and the local vertical.
- D - Specifies the RPM for the engine during the test.
- E - Specifies the steady-state speed recorded by the radar gun in the chase boat.
- F - Specifies the porpoising rate (in pitch cycles per second) if porpoising occurred.
- G - Comments as recorded by the driver or indication of planing.

ABYC Avoidance Course Report

This form reports on the speed and acceptance data during the running of the ABYC Avoidance course. The tests were run at the trim set for maximum speed. Figure 5-7 shows a sample report form which is keyed by circled letters to the explanation below:

- A - Specifies the direction on which the course was run. The West-to-East runs involved turns to the port side; East-to-West runs are starboard turns.
- B - Specifies the order in which the runs were made.

BOAT: ENGINE: TEST DATE:

TEST NUMBER: WATER CONDITIONS:

SPEED VERSUS RPM TEST

A TRIM: Max speed Motor Angle: B Transom Angle: C

RPM	D						
SPEED	E						
PROPOISING	F						
COMMENTS	G						

TRIM: Average Motor Angle: Transom Angle:

RPM							
SPEED							
PROPOISING							
COMMENTS							

TRIM: Under Motor Angle: Transom Angle:

RPM							
SPEED							
PROPOISING							
COMMENTS							

Figure 5-6

BOAT: ENGINE: TEST DATE:

TEST NUMBER: WATER CONDITIONS:

ABYC AVOIDANCE COURSE

A DIRECTION: West to East (Left turn)

RUN	SPEED ENTRANCE	SPEED EXIT	ACCEPTABLE (YES/NO)	COMMENTS
B	C	D	E	F

DIRECTION: East to West (Right turn)

RUN	SPEED ENTRANCE	SPEED EXIT	ACCEPTABLE (YES/NO)	COMMENTS

Figure 5-7

C - Specifies the speed at the entrance of the course, taken from the speed vs. RPM curve or from an actual reading with the radar gun.

D - Specifies the speed at the exit from the course, taken by personnel in the chase boat using the radar gun.

E - Specifies whether the boat stayed within the course (Acceptable = Yes) or left the course (Acceptable = No).

F - Comments of the test driver or chase boat personnel on the test.

ABYC Avoidance Course (Accelerometer Data) Report

This report is derived from data taken from the magnetic tape recordings of the accelerometer during ABYC Avoidance course runs. Figure 5-8 shows a sample report form which is keyed by circled letters to the explanation below:

A - Specifies the direction of the run. An East-to-West (EW) run involves a turn to the right to reach the avoidance marker; West-to-East (WE) runs involve a left turn.

B - The maximum acceleration experienced along the longitudinal axis of the boat while turning out to the avoidance buoy. The value shown is in g's.

C - The maximum acceleration experienced along the longitudinal axis of the boat while turning around the avoidance buoy.

D - The maximum acceleration experienced along the longitudinal axis of the boat while turning back into the course after passing the avoidance buoy.

E - Comments to the driver or notes of the data transcriber.

F - I - Identical to B - E except that the data are along vertical axis.

J - N - Identical to B - E except the the data are along the lateral axis.

N - Q - Identical to B - E except that the data are along the vertical axis at the bow of the boat.

BOAT: ENGINE: TEST DATE:

TEST NUMBER: WATER CONDITIONS:

ABYC AVOIDANCE COURSE
(Accelerometer Data)

RUN	DIRECTION		AT TURN	AT OFFSET	AT RETURN	NOTE
A		Longitudinal	B	C	D	E
		Vertical	F	G	H	I
		Lateral	J	K	L	M
		Bow	N	O	P	Q
		Seat Pad	R	S	T	U

RUN	DIRECTION		AT TURN	AT OFFSET	AT RETURN	NOTE
		Longitudinal				
		Vertical				
		Lateral				
		Bow				
		Seat Pad				

NOTES: V

Figure 5-8

R - U - Identical to B - E except that the data are taken at the driver's seat pad.

V - Notes or comments keyed to the data by a note number.

Turn Radius/ Quick Turn Tests Report

This form reports on the accelerations experienced during either Quick Turn or Turn Radius tests. It is derived from the accelerometer data on the magnetic tape and from the film data. Figure 5-9 presents a sample report with circled letters to key it to the explanation below.

A - Specifies the type of run, the amount and direction of helm change. For a Quick Turn, the entry is either QT CW or QT CCW for clockwise and counterclockwise turns, respectively. For Turn Radius, the entry will show a fraction, 1/4, 1/2, 3/4, and a direction. The fraction denotes the amount of helm turn; for example, 1/4 turn CW is a one-quarter turn of the helm clockwise.

B - Specifies the acceleration experienced along the longitudinal axis of the boat at the center of gravity. Two values are given: maximum (Max.) and steady-state (S.S.). The maximum value is always taken soon after the initiation of the manuever. The steady-state value is taken at that point where a steady condition appears on the strip charts. Both values are expressed in g's. Frequently, the steady-state will be sinusoidal about zero or an offset. In this case, the acceleration will be expressed as +X/-Y to provide the range of the motion.

C - Identical to B except that the accelerations are measured along the vertical axis.

D - Identical to B except that the accelerations are measured along the lateral axis.

E - Identical to B except that the accelerations are measured along the vertical axis at the bow of the boat.

F - Identical to B except that the accelerations are measured at the driver's seat pad.

G - The angle between the boat's longitudinal axis and the engine's thrust vector, expressed in degrees.

F - The time, in seconds, which it took the boat to turn 360 degrees.

BOAT: ENGINE: TEST DATE:

TEST NUMBER: WATER CONDITIONS:

TURN RADIUS/QUICK TURN TESTS

HELM CHANGE/ DIRECTION		LONGIT.	VERTICAL	LATERAL	BOW	SEAT	MOTOR ANGLE	360^0 TIME
A	Max. S.S.	B	C	D	E	F	G	H
	Max. S.S.							
	Max. S.S.							
	Max. S.S.							
	Max. S.S.							

Figure 5-9

Turn Radius/Quick Turn Test (Quadrant Citings) Report

The form is based on the observations of the chase boat personnel during the Quick Turn and Turn Radius tests. Figure 5-10 depicts a sample form keyed to the explanation below.

A - Specifies whether a Quick Turn or Turn Radius test was performed and the amount and direction of helm change. For a Quick Turn test, the entry is either QT CW or QT CCW for clockwise and counter-clockwise turns, respectively. For Turn Radius, the entry will show the amount of helm change (1/4, 1/2, or 3/4 turn) and the direction of the change (CW or CCW).

B - Specifies the entry speed obtained from either the speed vs. RPM curves or from a radar timing.

C - Specifies the exit speed of the boat, obtained from a radar timing.

D - Specifies the distance from the center of the course at which the boat crossed the first set of buoys. If the boat did not cross this set a dash is shown. If the boat crossed the buoy line but an accurate citing was not obtained, NA is specified. All distances are in feet.

E - G - Identical to D except that the citings are for quadrants 2, 3, and 4 respectively.

H - Identical to D except that the citings are for quadrant 1 after an entire 360 through the course. If quadrants 2, 3 and 4 are all shown as dashes, this indicates that the boat turned entirely within the first line of buoys, in which case this entry shows the distance where the boat crossed after 180° of turn.

I - Specifies the turn radius computed from the data shown.

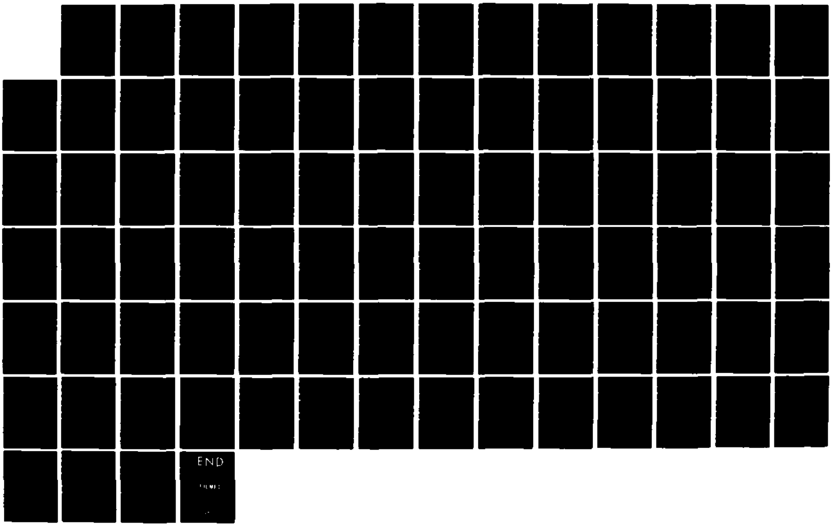
J - Comments. If the boat turned within a single line of buoys, this field contains the citing when the boat completed 360 degrees of turn and recrossed the buoys.

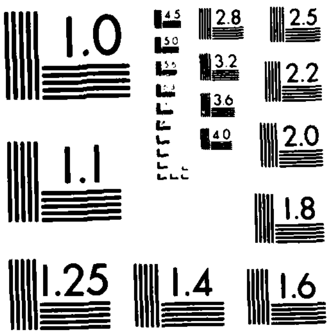
Zig Zag Report

This form reports on the results of the Zig Zag tests run on each boat/engine combination. Often, several Zig Zag runs were made with varying turn angles and direction of first turn. Figure 5-11 shows a sample report form which is keyed to the explanation below.

AD-A153 845 DEVELOPMENT OF ALTERNATIVES TO THE CURRENT SAFE POWERING STANDARD(U) IDEAMATICS INC WASHINGTON DC SEP 82 USCG-D-3-85 DTCG23-80-C-20003 2/2

UNCLASSIFIED F/G 13/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963 A

BOAT: ENGINE: TEST DATE:

TEST NUMBER: WATER CONDITIONS:

TURN RADIUS/QUICK TURN TEST

HELM CHANGE/ DIRECTION	SPEED ENTER	EXIT	QUADRANT CITINGS: 1	2	3	4	1	Radius	Comment
A	B	C	D	E	F	G	H	I	J

Figure 5-10

BOAT: ENGINE: TEST DATE:

TEST NUMBER: WATER CONDITIONS:

ZIG ZAG TEST

Run Number:

TURN NUMBER	TIME FROM START	NEW MOTOR ANGLE	TIME TO CHANGE MOTOR	HEADING CHANGE	COMMENTS
A	B	C	D	E	F

Figure 5-11

A - Specifies the turn number or (for START) the initial rudder position.

B - Specifies the number of seconds from the last turn in the left corner and the total number of seconds in the lower-right corner.

C - Specifies the motor angle at the start of the turn, in degrees.

D - Specifies the amount of time which it took to turn to the motor angle given in C.

E - Specifies the heading change, in degrees, undergone during the previous turning manuever.

TEST REPORT ON SMALL BOATS

Included in the testing program were two small boats: a 12-foot Laminated and a 10-foot-9-inch Sears. These boats were slated to be run with both 7.5 and 10 HP engines. Before running the tests on these boats, it was apparent that the weight of the standard instrumentation package (which exceeded 120 pounds) would adversely affect the performance of these boats. Thus, it was determined to run these boats with only the film camera aimed at a magnetic compass. To increase the amount of data, videotape recordings of the runs were made.

Both boats were overpowered and unstable even with the smallest engine available to the testing program: a 7.5 HP Johnson. The rated horsepowers of the Sears and Laminated are 5 and 6, respectively. Neither boat would initially run in a straight line, and only after a considerable amount of driver acclimatization had occurred could any testing be attempted.

The speed runs were completed without incident with the Sears obtaining a top speed of 22 mph and the Laminated a top speed of 18 mph.

The Laminated was the first boat to attempt the ABYC Avoidance course. On the first run, the boat turned over and the movie camera broke free of its restraints and was lost in the bay. Neither boat could complete

the ABYC Avoidance course at anything near the maximum speed unless a large amount of "body english" or weight shifting was utilized by the test driver. The boats would successfully turn off course and toward the offset buoy but would flip over when the turn around the buoy was attempted. Both boats successfully completed the course when the speed was reduced to 9 mph and the boats were no longer on plane.

For the Quick Turn and Turn Radius tests, a substitute for the turning of the helm had to be utilized. In these tests, the tiller was turned all the way to lock for the Quick Turn and the Turn Radius and one-half way to lock for a second Turn Radius test.

Both boats successfully completed boat turning tests. When the tiller was turned to the lock, the boat would turn within 10 to 15 feet, literally turning on itself. At the same time, the boat's forward velocity was negligible or practically zero. When the tiller was turned one half the way to lock, the boats turned within the first measuring buoy, 30 feet from the starting point. Again, the forward velocity was reduced to but a few miles per hour.

In all during the running of these two boats with the 7.5 HP engines, the boats flipped over at least five times. Given the highly unstable performance with this engine, it was not felt safe to attempt to run with the next more powerful one, a 10 HP engine.

TEST RESULTS ANALYSIS

As a whole, the testing program collected a vast amount of data. Accelerations, velocities, headings, citings, and timings have been captured for the wide spectrum of boats and engines within the scope of this project. This section examines the testing in terms of the validity of the tests

and the completeness of the data. In this analysis, validity is decided on the basis of engineering judgment and repeatability. Each of these factors is discussed below.

The primary factor in judging the validity of any testing is to compare the results to known or observed phenomena and to ensure that the data behave as it is known that they should behave. The results of this testing appear to satisfy these conditions. There are many examples of this consistency in the data. For example, the pattern of the accelerometer readings follows the known motions of the boat. In the ABYC Avoidance course, the lateral accelerometer first displays an acceleration in one direction followed by an acceleration in the opposite direction, and finally one in the original direction. In most of the Turn Radius tests, the vertical accelerometer shows a steady-state sinuisoid which comports well with the steady state which is usually observed.

Not only are the directions of the accelerations consistent with observed fact but so are the magnitudes. One would seriously doubt lateral accelerations which steadily exceeded 5 g's but such are not the case here. Although an occasional jolt or transient spike may reach such a magnitude, the results of this testing show reasonable g levels. (Of course, it remains for further analysis to determine whether the g forces encountered are tolerable). Likewise, the longitudinal accelerometer exhibits a small deceleration upon entering a turn which is totally consistent with the speed loss measured via radar.

Similar data consistencies abound in the accelerometer, film and manually recorded data. This is not to say that all the data are immediately consistent upon initial inspection, for there are a number of test results which only a fuller analysis can explain. (For example, during some turns

the lateral accelerometer oscillates about zero). However, the vast majority of the data do satisfy a preliminary check for engineering consistency.

The second most important analysis of a testing program is whether the test results are repeatable. Non-repeatable results considerably diminish reliance in the test methods, design or execution. Here again the results of the boat testing appear satisfactory or better. In numerous instances in all the tests, results from different runs of the same boat/engine under similar conditions relate quite well to each other.

Repeatability is probably best demonstrated by showing examples. An examination of any of the Speed versus RPM curves demonstrates this amply. Almost invariably, the curves for the same boat/engine have the same shape curves and nearly the same magnitudes. A similar result is obtained when ABYC Avoidance course Quick Turn and Turn Radius manual and film results are examined. Any differences which do appear are usually minor and well within the margin of error. A larger discrepancy between results does appear when the accelerometer data are examined. Although the accelerometer data are often very closely related, especially in the longitudinal and lateral directions, there are some significant departures. Many of these differences among the accelerometer data are a result of the microscopic look at the boat's motion which the accelerometers provide. Simply hitting a wave during a manuever causes a spike in the accelerometer reading which may or may not be matched during the rerun of the same boat.

Finally, although this report and the raw data upon which it is based provide enormous amounts of data, not all the data sought have been obtained. As mentioned earlier, the two small boats could not be run with the higher horsepower engines as originally planned. One boat, the Seminole, had to be eliminated from the testing because of leaks and water damage. Even

within tests which were conducted, some data were occasionally missed. The testing itself is the primary cause of the missing data, for it is the harsh conditions of the tests which caused breakdowns in the equipment. Nearly every piece of electronic equipment had to be either repaired or replaced during the testing. This resulted from the repetitive high g forces to which the equipment was subject, and from the wet environment that is a necessary byproduct of on-the-water testing. As a result of these factors, an accelerometer is sometimes not recorded correctly or the film is too jittery to be read. However, on the whole, the selected instrumentation provided the desired data at most times.

DATA PROCESSING

Once the test data were all assembled, they could be entered into the computer, processed, and analyzed. Accordingly, coding sheets were devised and data entry performed. Coding sheets and abbreviations are to be found in Appendix B. Some additional data were developed: center of gravity information was added; speed lost on the ABYC and turn tests was calculated; the turn radii for the quarter-, half-, and three-quarter-helm-change turns were segregated. In addition, a turning summary was compiled, which facilitated comparison of turn angles, radii, times, helm changes, and speeds.

After the data had been entered and checked and rechecked for accuracy, they were submitted to computerized cross-correlation analysis. The analysis provided a number of statistical comparisons. The mean, standard deviation, and range of each parameter were computed. The computer program provided a correlation coefficient and a significance probability for each correlation.

In addition to calculating correlations, probabilities, means, and standard deviations, the computer program also calculated several variables which were

then included in the correlations and means calculations. A list of these variables is included as Appendix C.

After these steps, analysis of the data could be conducted.

DATA ANALYSIS

Statistical analysis of the test data base shows the following means.

Boat Parameters

The mean test boat measurements are:

- o 17' 5" long (range 15' 2" to 19' 5")
- o 5' 8" wide at the maximum chine beam (range 4' 7" to 7' 1")
- o 16 " deadrise (range 8" to 25")
- o 1405 pound capacity (range 1000 to 1850)
- o 2734 pounds hull weight (range 2307 to 3160)
- o 60" longitudinal center of gravity (range 47" to 77")
- o 144 rated horsepower (range 70 to 198)
- o 162.8 mounted horsepower (range 25 - 235)

As stated in the PRAM analysis, the test boats are somewhat larger than the PRAM boats, and the engines more powerful. Compared with the boat universe at large, the test boats are on the high end of the powering scale. The National Boating Survey of 1976 shows 450 out of 1,862 bowrider runabouts (24 percent) to have horsepowers over 100 (most are 51 to 100), while 509 out of 1,701 non-bowrider runabouts (29 percent) are over 100 (507 have 51 to 100 horsepower; 490 have 31 to 50 horsepower).

Speed Data

Consideration of boat activity shows us that the mean maximum speed of all test boats is 45.34 miles per hour (range 33 to 57 mph), and the mean

speed at which the boats plane (at maximum trim) is 18.55 (range 9 to 27). These speeds can be compared with the mean speed-in on the ABYC course--42.48 (range 22 to 53)--and the mean speed-in on the turn tests--43.6 (range 29 to 53). Such a comparison suggests that the test-driver made a good effort to initiate all tests near maximum speed.

Further consideration of speed data show that the mean speed lost on the ABYC tests was 3.09 miles per hour, while the mean speed lost on the turn tests was 9.15 miles per hour, a notable difference. As expected, however, a corresponding difference in lateral and vertical accelerations between the ABYC and turn tests reflected the greater speed lost on the turn tests.

Acceleration Data

The turn test acceleration data are, on the whole, more dramatic than the ABYC data, although both readings record maximum, transient accelerations, while the turn test data illustrates steady state accelerations as well. Nonetheless, the mean acceleration forces are higher on the turns than on the ABYC, and the top transient accelerations are must greater, with several 2-, 3-, and 4-g accelerations recorded. As noted in Chapter II, these forces, according to whatever scale of evaluation one uses, are enough to represent serious hazard for passengers and operators. They are, to be sure, transients, and quickly recovered from. But, occurring sharply and suddenly as they do, with the possibility of combining with other forces, they well illustrate the contingent, chancy nature of the boating accidents, a characterization we observed in the PRAM study.

The data recorded concerning acceleration do not represent a thorough picture of all acceleration forces. Machines did not always record (they, too, are subject to the g forces); sometimes that which was recorded could not be read, for a variety of reasons. One boat, the Sterling, swamped in the course of testing, an event which greatly reduced the reliability of the data available from its performance. What this means, on the whole, is that acceleration forces are, if anything, underrecorded and underrepresented. Mean acceleration data are provided in Table 3-1, p. 3 - 14, and are discussed in the following sections.

Longitudinal Acceleration

Longitudinal acceleration on the ABYC tests was relatively mild. The highest single reading is 1.25 g at the turn-point (return and offset have lower highs, although the mean offset is higher than the mean return and mean offset). Longitudinal acceleration on the turn tests, however, was somewhat higher, with a mean maximum g force of 0.38 g.

Vertical Acceleration

Vertical accelerations on the ABYC tests were stronger than the longitudinal and weaker than the lateral. Again, the highs on the ABYC test did not exceed 1.75 g, while the vertical high on the turn test reached 4.7 g. The bow accelerations, similarly, while moderate on the ABYC, also showed a sharp, transient 4.2 g on the turn tests. Bow and seat readings exist only on the ABYC turn-point, and the turn tests.

Lateral Acceleration

Lateral accelerations were the strongest of the accelerations operating on the ABYC tests. Indeed, the average lateral accelerations at the turn-point and offset-point were around three-quarters of a g, while the mean lateral acceleration at the return point was a high 0.92 g. One transient

reading of 4.9, at the offset point, was the highest g recorded during the ABYC tests. As for the turn tests, the lateral accelerations recorded averaged slightly lower than the average vertical accelerations, 0.74 g lateral as opposed to 0.89 g vertical. Turn-test lateral accelerations are comparable to ABYC turn-point and offset readings, but lower than return readings.

Acceleration Summary

Acceleration data provided by the testing program are useful data. They can be considered reliable, because quick-turn and turn-radius tests track the ABYC tests insofar as accelerations and speed losses seem to be parallel. They are further corroborated by IDEAMATICS' research in acceleration forces, and by the evidence PRAM has given us concerning the events which lead to recreational-boat-use tragedies, that is, people thrown overboard, on to the deck, into equipment, or away from controls. PRAM shows us that accidents occur because of sudden accelerations, and the testing program shows us that sudden accelerations exceeding 1 g (and as high as 4.9 g's) are not unusual in recreational boat use. In fact, out of 220 ABYC turn tests, acceleration forces of 1 g or greater were recorded 118 times, a figure which does not include those data lost to machine malfunction or other marine mishap.

Figure 5-12 presents the incidence of high acceleration forces per boat/engine combination during the ABYC tests and the turn tests.

Turn Data

Statistical analysis of the Turn Test data shows us that two-thirds of the turns were made at one-half-helm turn, slightly over one-sixth were made at three-quarters-helm turn, and slightly fewer than one-sixth were made at one-quarter-helm turn. The mean motor-turn angle was 8.9 degrees (range 4 degrees to 15 degrees). The mean turn radius was 263.11; broken down into degrees of tightness, mean radii were:

- at one-quarter-helm, 353.57' (range 225' to 455')
- at one-half-helm, 277.75' (range 90' to 480')
- at three-quarters-helm, 193.39' (range 80' to 420')

The mean one-quarter-helm turn's radius was 75.82' larger than the radius of the one-half-helm turn, whose radius was, in turn, 84.36' larger than the radius of the three-quarter-helm turn.

Individual Boats

In addition to making a statistical analysis of the parameters and actions of all the test boats, IDEAMATICS analysts also examined the actions during the ABYC tests and turn tests of each boat individually. The summaries of those actions are given in the following pages. The boats are arranged in alphabetical order. A summary of acceleration forces is presented in Table 5-12.

Boat/Engine Combination	ABYC Tests		Turn Tests	
	Number of Tests	Incidence of Acceleration 1g of Higher	Number of Tests	Incidence of Acceleration 1g of Higher
Angler 115E	9	1	1	0(no data)
Angler 150M	9	2	14	7
Bonito 55E	3	3	0	0
Bonito 75E	10	3	12	5
Caribe 198M	4	7	16	17
Dolphin 200M	4	0(no data)	14	0(no data)
Dolphin 235J	7	11	21	15
Hawaiian 140	7	3	16	15
Higgscraft 150M	5	2	12	8
Higgscraft 200M	2	0	8	0(thin data)
Hydrasports 115E	6	0	7	0
Hydrasports 150M	6	2	10	9
Sterling 150M	3	2	6	4
Sterling 235J	2	0	6	2(swamped)

Table 5-12

INCIDENCE OF HIGH ACCELERATION FORCES

DURING ABYC TESTS AND TURN TESTS

ANGLER
(V-hull)

In spite of the fact that 5 of the 18 ABYC tests were unacceptable, only 2 high g readings were recorded for this boat. As for the turn tests, one aborted QT/CCW test threw the driver, but the boat shut off via a kill switch. In fourteen turn tests, high g readings (1 g or higher) occurred 7 times, including one extreme reading of 3.9 (bow acceleration). Also noteworthy were five instances of pronounced speed loss of 15 to 20 mph during the turn tests.

Notes:

Run 2 handled much better than Run 1.

No chine walking.

ABYC tests (115 hp): 5 acceptable, 4 unacceptable
ABYC tests (150 hp): 8 acceptable, 1 unacceptable

Turn data (150 hp):
(available for 150 hp only)

Speed-in: 48 mph

Mean radius at half-helm: 282.5'

<u>BONITO</u>

(tri-hull)

On ABYC tests, the lower boat/engine combination (55 hp) showed 3 high g readings (1 g or higher) in lateral acceleration, but the higher combination (75 hp) showed 3 high g readings in the longitudinal and vertical accelerations. Performances on the turn tests were fairly calm, with low readings on the first six tests, while the last six tests showed 5 high g readings.

ABYC tests (55 hp): 2 acceptable
ABYC tests (75 hp): 6 acceptable

Turn data (75 hp)
(available for 75 hp only)

Speed-in: 35 mph

Mean radius at half-helm: 268.8'

NUCO/CARIBE

(I/O; Deep-V)

Although this boat's maximum speed is the lowest of all the boats (39 mph) it had many high g readings: 7 high g's in 4 ABYC tests, and 15 high g's in 13 turn tests. Six of the former were in lateral accelerations, while 7 of the latter were vertical, and 5 lateral. One turn test had a steady-state reading which vacillated between +1g and -1.2g.

Notes and driver comments

Driver hit head on windshield; felt he was being thrown out.

Nearly spun out at 60^{o}.

Driver cut elbow on control due to rough turn.

On ABYC course: power steering on boat; tends to oversteer through course. (Run 1)

On ABYC course: oversteered through course. (Run 2)

ABYC tests: 4 acceptable

Turn data:

Speed-in: 39

Mean radius at half-helm: 120'

See note re I/O boat performance on Hawaiian summary.

DOLPHIN

(Deep-V)

The ABYC tests and turn tests for the lower-powered combination (200 mph) have no accelerometer data because of machine malfunction. The bow accelerometer also malfunctioned during some of the later turn tests with the stronger engine (235 mph). In spite of this lacuna, the boat registered 11 high g's in 7 ABYC tests, and 15 high g's in 21 turn tests, the roughest of the boats. 7 high g's occurred in the ABYC lateral accelerations. Also noteworthy is the fact that the boat experienced consistently high speed loss during the turn tests (15-20 mph).

Notes

Run 2, J235 engine: waves in course affected results, driver "hang-on."

ABYC tests (200 hp): 4 acceptable
ABYC tests (235 hp): 7 acceptable

Turn data (200 hp):

Speed-in: 49

Mean radius at half-helm: 261'

Turn data (235 hp):

Speed-in: 45

Mean radius at half-helm: 316.7'

HAWAIIAN

(I/O; Deep-V-hull)

The ABYC tests were relatively calm, save for 3 high g readings. The turn tests, however, showed 15 high g readings out of 16 tests, with lots of strong readings in the bow accelerations (1.25, 1.00, .85, .75, .70, .70, .60), and the observation "severe chatter."

It should be noted that I/Os are prone to high bow acceleration because the bows ride high. Likewise, they have a lower center of gravity and therefore "dig in" more, consequently producing higher g forces. Furthermore, because they are heavy, they have lower entry speeds and shorter radii. (See also the Nuco/Caribe.)

ABYC tests: 7 acceptable

Turn data:

Speed-in: 36 mph

Mean radius at half-helm: 202.5'

HIGGSCRAFT

(deep-V)

Except for 4 extremely high g readings (around 4 g's each, possibly the result of striking wakes), there were no high g's during the ABYC tests. (It should be noted that "turn" and "return" accelerometer markings are not given on Run 1 charts.) There were very few readings recorded on the tests run with the stronger engine (200 mph). The turn tests showed 8 high g's out of 20 tests.

ABYC tests (150 hp): 5 acceptable
ABYC tests (200 hp): 2 acceptable

Turn data: (150 hp):

Speed-in: 48 mph

Mean radius at half-helm: 410'
(This figure is based on only 2 readings, both of them suspect. More reliable is the mean radius at three-quarter-helm, 292.5'.)

Turn data: (200 hp):

Speed-in: 53 mph

Mean radius at half-helm: 245'

HYDRASPORTS

(semi-V-hull)

The boat showed two high g readings during the ABYC tests. There may have been more, but recording malfunction occurred. During the turn tests, the higher boat engine combination (150 hp) showed 9 high g's during 10 tests, 5 of them occurring in the bow acceleration (plus values). (One was an extreme 4.2 g.) Although the boat seemed to corner well and had the most coordinated turn, it hit the island three times during the turn tests. One ABYC test was unacceptable.

ABYC tests (115 hp): 6 acceptable, 1 unacceptable
ABYC tests (150 hp): 6 acceptable,

Turn data: (150 hp):
(115 hp combination not adequately designated)

Speed-in: 50 mph

Mean radius at half-helm: 407.5'

SPORTSMAN

(flatbottom)

Results for this boat are limited: the boat is so small that the instrumentation packages are too heavy to place in it. Consequently, there are a limited number of data, all derived from a run with the E25 engine. Four ABYC tests were performed, two of which were unacceptable. There were three turn tests, none of which yielded any data.

ABYC tests: 2 acceptable, 2 unacceptable

Turn data: (25 hp):

Speed-in: 29 mph

Mean radius at half-helm: 237.5'

STERLING
(tunnel)

With 2 high g readings on the ABYC tests and 6 high g's during the turn tests, this seems to be an average sort of performance, in spite of this being a heavily powered boat. But the boat did swamp, and the accelerometers were non-functioning much of the time during the tests with the more powerful engine (235 hp). One ABYC test was unacceptable.

ABYC tests (150 hp): 2 acceptable, 1 unacceptable
ABYC tests (235 hp): 2 acceptable

Turn data (150 hp):

Speed-in: 50

Mean radius at half-helm: 480' (only one reading)

Turn data (235 hp):

Speed-in: 50

Mean radius at half-helm: 305'

STATISTICAL CORRELATIONS

After examining the means and standard deviations and making individual analyses of each boat, IDEAMATICS' analysts performed a computer-assisted statistical cross-correlation of all the data. This study, which related the data of each category with data of all other categories according to frequency, was useful is many ways.

First, it served to verify the consistency of the test data. That is, the table of correlations included a high correlation between the category of boat length and rated horsepower. We know this correlation to be true in fact (it is the present recreational boating horsepower formula); the fact that the high correlation occurred on the correlation table indicates that the correlations were correctly performed.

The second way in which the table of correlations was useful was that it served to validate previous hypotheses. In other words, it confirmed results which might be expected from earlier research. The table showed, for instance, that there was a strong correlation between lateral acceleration and boat velocity, a fact which principles of marine architecture and of acceleration studies would lead one to believe.

The third use for the correlation table lay in its suitability as a predictive tool. In addition to correlating data from the test program and the boat and engine parameters, the computer analytical system enables generation of variables from those data. For instance, it was possible to generate variables representing such concepts as Crouch's number (maximum speed times the square root of the product of total weight divided by engine horsepower), a speed coefficient (.8954 times maximum speed, divided by the square root of chine width), and the factor used in the present powering formula (transom width divided by 72, times length). These variables, once generated, were

then in turn correlated with all the other data categories. By this method, analysts were able to identify relationships which might be useful to pursue, as well as those which showed little promise.

These observations and analysis made, building of the mathematical model commenced, a step which will be examined in the next chapter.

REVIEW OF PROJECT ACTIVITIES

In reviewing the course of this project, IDEAMATICS recognizes that there were delays and difficulties. The following section will discuss ways in which those delays and difficulties can be minimized in future testing programs.

Research and PRAM Studies

Performing the literature searches for the background provided no difficulty (other than the frustrations engendered by a paucity of relevant material). However, difficulties arose once the assembly of the two large data bases was approached. The first data base -- the PRAM data -- proved difficult to assemble because of the incomplete nature of accident reporting. For the data amassed by accident reporting to be useful, reporting sheets must be filled out accurately and completely, an infrequent occurrence. Reporting officers should be encouraged to strive for more complete reporting.

Testing Program

The amassing of the second data base, i.e., the testing program, encountered difficulties which might be avoided in a future program by improvements in the following areas.

Location

Such tests should be done on an inland test course. Too many working days were lost to the variability of Tampa Bay's chop and tides. Courses should be selected that are not affected by tides.

Observation

Test runs should be filmed from a fixed point on shore, preferably from an elevation, such as a high platform. All test-data recording could benefit from a greater number of observers positioned at different points along the courses. At the very least, there should be a person at either end of each course.

Instrumentation

Filming instrumentation can only be relied upon for gross outlines. Sun glare and the combined jerkiness of the boat's sudden motions and of the slowly recorded film caused great difficulty in abstracting data. If film is used, it should be run at a very fast speed in order to catch the motions of a rapidly changing indicator such as the pitch-roll indicator. Instead of being filmed, instruments should all be attached to multi-track magnetic tape and translated into strip charts. A further delay caused by instrumentation problems arose from the fact that the batteries and engine did not provide enough power, and an auxiliary motor-generator was required. Efforts should be made to obtain a lighter instrumentation package so that small boats (i.e., Johnboats) can be fully tested.

Test-Boat Selection

There are two improvements that might be made in this area. The first is to make a greater effort to select test boats which would parallel the boat profile of the PRAM boats, i.e., shorter boats, with more representation of V's, semi-V's and tri-hulls. The second way to produce data more amenable to meaningful analysis might be to include a few known "hot" boats, a few failures to provide comparison with the successful boats.

Boat Universe

One final improvement that would greatly help in the analysis of both the PRAM data base and the testing data base is to obtain an accurate and

detailed picture of the boat universe. Both the PRAM study and the test-boat study could benefit from comparison with the extant boat population, if the population of the extant boat population were known in sufficient detail: length (to the foot), hull-shape, horsepower, manufacturer.

CHAPTER VI
POWERING DATA ANALYSIS

The information collected during the first six tasks of the Current Safe Powering Standards study is reported in Chapters II through V. These data are the input to and basis of the analysis described in this chapter. Subsequent sections of the chapter detail the analytical procedures adopted for the study, the identification of significant factors, the development of parametized powering formulae, and the validation of a test course and formula approach.

ANALYSIS PROCEDURES

Six separate analytical techniques were employed to examine the safe powering standard:

- o theoretical analysis of maneuvering
- o statistical analysis of accident data
- o sensitivity analysis
- o curve fitting to experimental data
- o empirical validation
- o scenario evaluation

Each of these techniques provided information about the maneuvering performance of small recreational boats.

Theoretical Analysis of Maneuvering

The theoretical analysis is described in detail in Chapter II. This examination of the physical processes which influence the maneuvering of a small boat resulted in the identification of those factors, or

variables, whose values are expected to indicate the performance of any specific boat. Three factors were focused on as a result of the examination:

- o maximum speed
- o dynamic instability as evidenced by oscillations
- o turn radius

Statistical Analysis of Accident Data

A thorough analysis of Boating Accident Reports (BARs) was performed to determine the predominent causative factors of powering-related accidents. This analysis is discussed in Chapter IV. The result of statistically analyzing accident data was the enumeration of fifteen factors which can be measured and can be related to specific accident causes. Additional research into probable values for each factor showed that accelerations are the most definitive measure.

Sensitivity Analysis

The data collected during the testing program were reviewed and analyzed as described n Chapter V. All data points were evaluated for correlation to the identified "target" variables (e.g., speed, radius, acceleration). New variables which are combinations of data elements were calculated. The variability of data elements (means and standard deviations) was evaluated both to indicate where differences among boat/engine combinations were significant, and to illustrate which elements were insensitive to changes in boat characteristics.

Curve Fitting to Experimental Data

The bulk of the efforts performed during Task 7 fell under the auspices of fitting the test data to hypothesized equations. Mathematical models of the "target" variables were postulated and then evaluated against the collected data. The evaluation consisted of using a least squares linear regression of the experimental data.

The review of test data required an examination of the consistency of the test results as well as the comparison of the test results to the PRAM data. This examination indicated that efforts should be concentrated on the lateral acceleration. First, the lateral acceleration measurements and the speed measurements were the most consistent data points across all of the tests for all of the boat/engine combinations. Second, the lateral accelerations measured during the testing program exhibited the highest average values and the greatest divergence from the tolerances established by corollary research. Third, most of the PRAM accidents showed that problems occurred whenever lateral acceleration was combined with other factors.

The testing program verified the perception obtained from reviewing accident reports that lateral acceleration was a significant accident causation factor. The tests replicated the conditions anticipated by accident categories, particularly falls overboard.

The results of the curve fitting efforts are described more completely in a subsequent section of this chapter under the title "Formulae Development." However, it was important during the analysis to recognize the fact that limiting lateral acceleration would necessitate

the control of maximum speed and/or minimum turn radius [1] (i.e., $a = V^2 / r$). This leads to the conclusion that while maximum lateral acceleration can be used to define an upper bound for the regulation of a recreational boat, maintaining the ability to maneuver (i.e., avoid accidents) must become the lower bound for regulation.

Empirical Validation

The results of the tests performed for the selected boats were compared to those predicted by the formulae. In each instance the empirical data verified the proper application of the formulae with realistic, replicable information. A dimensional analysis of each equation was made to guarantee valid results.

Scenario Evaluation

The final analytical technique was to evaluate the formulae in light of specific accident scenarios. This review determined the logic of the developed formulae and ensured their practical use.

The purpose of this rigorous evaluation was to identify those physical characteristics of the boat which, when considered in conjunction with engine horsepower, can predict the maximum speed and expected turning radius. These, in turn, predict a measure of the expected lateral acceleration.

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[1] The turn radius in a steady state turn is not identical to the transition turn radius which occurs initially during a turn and which generates the highest values for lateral acceleration. However, the two variables are integrally related. It is felt that the steady state turn radius is a reliable predictor of the dynamic, instantaneous radius which can only be otherwised obtained with great difficulty and expense.

SIGNIFICANT FACTORS

Theory shows that the maximum speed of the boat is dependent upon the installed horsepower and the displacement of the boat (i.e., the total weight of the loaded boat) where the constant multiplier is a function of the boat design (i.e., hull shape). Examination of the experimental data shows that Crouch's formula gives an adequate estimate of maximum speed while allowing for a simplistic formulation of two independent variables.

Examination of the turning radius at a predetermined motor turn angle provides a relative measure of the acuteness of a turn. This "turn severity" is a function of the physical shape of the boat and the profile presented to the water by the planing surface. The shape of the planing surface in contact with the water must be evaluated throughout the turn, particularly the initial moments prior to steady state. Such a process is complex and difficult to simulate mathematically from a geometric and temporal aspect. However, if it is assumed that the actual turning radius is an indicator of "turn severity," then a predictor of turn radius can be used to predict the relative severity of turns. Such a "turn severity measure" is dependent upon the basic characteristics which define the shape of the planing surface of the craft.

The slenderness ratio (SLR) defines the geometry of the boat overall and is the ratio of the beam to the length of the boat. The most invariant measures of boat beam and length are the beam at the maximum chine (BCH) and the distance of the center of gravity from the transom (LCG). These independent variables were chosen over more generalized

variables, such as transom width and boat length, because they more accurately define the size of the planing surface and are not affected by ornamentation or cosmetic design variances.

The hull shape measure (HSM) defines the profile of the boat's planing surface and is the ratio of the deadrise angle to the length of the boat. The deadrise angle (DEDR) measured at the transom gives an indication of the shape of the hull and its "bite" (e.g., semi-V, deep-V, flat bottom, etc.). The distance from the center of gravity to the transom (LCG) can be used to describe effective boat length.

The slenderness ratio and the hull shape measure are inversely proportional to the turn radius which can be obtained at maximum speed for a given motor turn angle. The slenderness ratio is dimensionless while the hull shape measure has dimensions of $(\text{feet})^{-1}$. The multiplication of their inverses is dimensioned in feet which is consistent with measured turn radii of the test boats.

FORMULAE DEVELOPMENT

A formula approach to evaluate safe powering limits is feasible using the significant factors described previously. The approach outlined in this section has three major components. First, a relationship for maximum speed is derived. Second, a relationship for the turn severity measure is formulated. Third, the results of the first two components are combined to postulate an acceleration measure that predicts maximum possible lateral acceleration. Table 6-1 shows the observed values of the significant factors considered for specification of boat/engine combination characteristics. These factors are:

- o installed engine horsepower

Boat/Engine Combination	Mounted Engine Horsepower	Total Weight (lbs)	Beam at Chine (in.)	Length from Transom to Center of Gravity (in.)	Angle of Deadrise (^{o})	Square root of Mounted HP divided by Total Weight	Slenderness Ratio	Hullshape Measure
Angler/115E	115	2725	63.25	60	13.5	.205	1.054	.0039
Angler/150M	150	2803	63.25	54	13.5	.231	1.054	.0044
Bonito/55E	55	2087	54.5	64	11	.162	0.852	.0030
Bonito/75E	75	2112	54.5	61	11	.188	0.852	.0031
Caribe/198	198	3160	71	50	16.5	.250	1.42	.0058
Dolphin/200M	200	2972	69.25	65	25	.259	1.065	.0067
Dolphin/235J	235	2990	69.25	61	25	.280	1.065	.0072
Hawaiian/140	140	2784	--	65	16	.224	--	.0043
Higgscraft/150M	150	2683	71	55	16	.236	1.291	.0051
Higgscraft/200M	200	2662	71	58	16	.274	1.291	.0048
Hydrasports/115E	115	2497	61.25	69	10	.215	.996	.0025
Hydrasports/150M	150	2574	61.25	61.5	10	.241	.996	.0028
Sterling/150M	150	2544	72	67.5	8	.243	1.067	.0021
Sterling/235J	235	2560	72	67.5	8	.303	1.067	.0021

Table 6 - 1

BOAT/ENGINE CHARACTERISTICS

- o total loaded weight in pounds
- o beam at the maximum chine in inches
- o distance of the center of gravity from the transom in inches
- o angle of the deadrise at the transom in degrees
- o horsepower load
- o slenderness ratio
- o hull shape measure

Maximum Speed

The basis of the estimation of maximum speed is Crouch's formula. To determine a value for the constant, a least squares regression of observed maximum speed on the horsepower load results in:

$$V_m = 14.91 + 132.12 \left(\frac{EHP}{TWT}\right)^{\frac{1}{2}} \qquad (1)$$

where V_m predicted maximum speed in mph

EHP installed engine horsepower

TWT total loaded weight in lbs (boat + engine + equipment + passengers)

The intercept of 14.91 mph and the coefficient of 132.12 define the line of regression between maximum speed and horsepower load. The coefficient of correlation for this formulation and the test data is 0.8088 while the standard error of estimate is 5.42 percent.

The determination of predicted maximum speed can be reduced to graphical form as shown in Figure 6-1. The user can locate the total weight of a boat on the x-axis, read vertically to the desired horsepower curve, and read off the y-axis the associated value for predicted maximum speed.

The Severity Measure

The formulation of a turn severity measure as a predictor of turn radius was also developed through a least squares regression. The

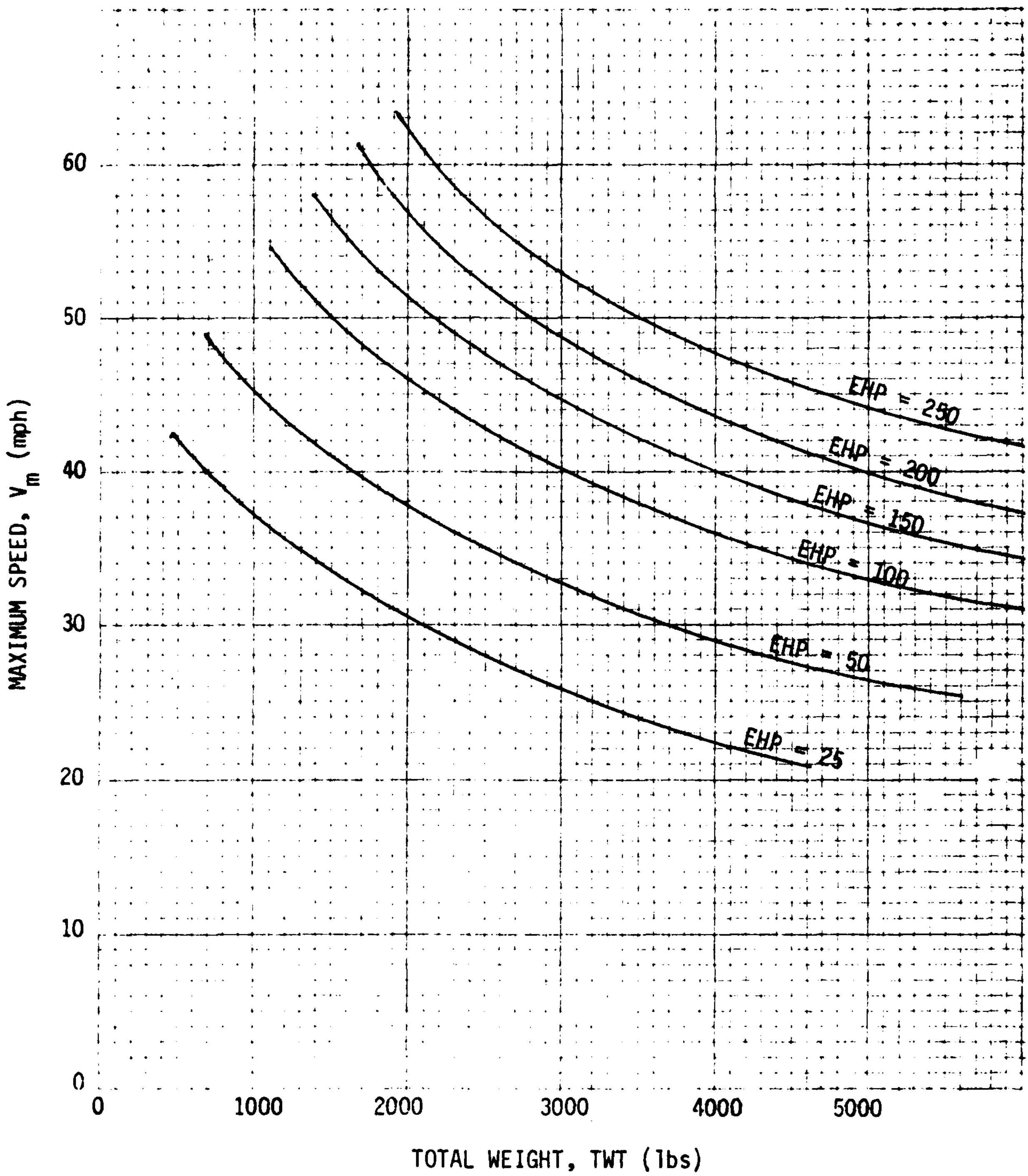


Figure 6 - 1

PREDICTED MAXIMUM SPEED VERSUS TOTAL WEIGHT AND ENGINE HORSEPOWER

regression model postulated turn radius at maximum speed and half-helm as inversely dependent on slenderness ratio and hull shape measure. The resulting equation is:

$$TSM = \frac{0.725}{SLR \times HSM} + 21.13 \qquad (2)$$

where TSM = turn severity measure in ft

SLR = slenderness ratio

HSM = hull shape measure

The independent variables are derived from typical boat characteristics as follows:

$$SLR = BCH \,/\, LCG \qquad (3)$$

where BCH = Beam at the maximum chine in inches

LCG = distance from the center of gravity to the transom in inches

$$HSM = DEDR \,/\, LCG \qquad (4)$$

where DEDR = angle of the deadrise at the transom in radians

The intercept of 21.13 feet and the coefficient of 0.725 define the line of regression between turn severity measure (a predictor of turning radius) and the boat characteristics of slenderness and hull shape. The correlation coefficient for the formulation and the test data is 0.7577 while the standard error of estimate is 13.92 percent.[2]

The determination of the turn severity measure can be reduced to graphical form as shown in Figure 6-2. The user can locate the slenderness ratio of a boat on the x-axis, read vertically to the desired hull shape curve, and read off the y-axis the associated value of turn severity.

* Improvements to the estimating equation can be made through the introduction of additional characteristics. However, the complexity to the user (e.g., boating public) is increased without a commensurate increase in accuracy of the predicted lateral acceleration.

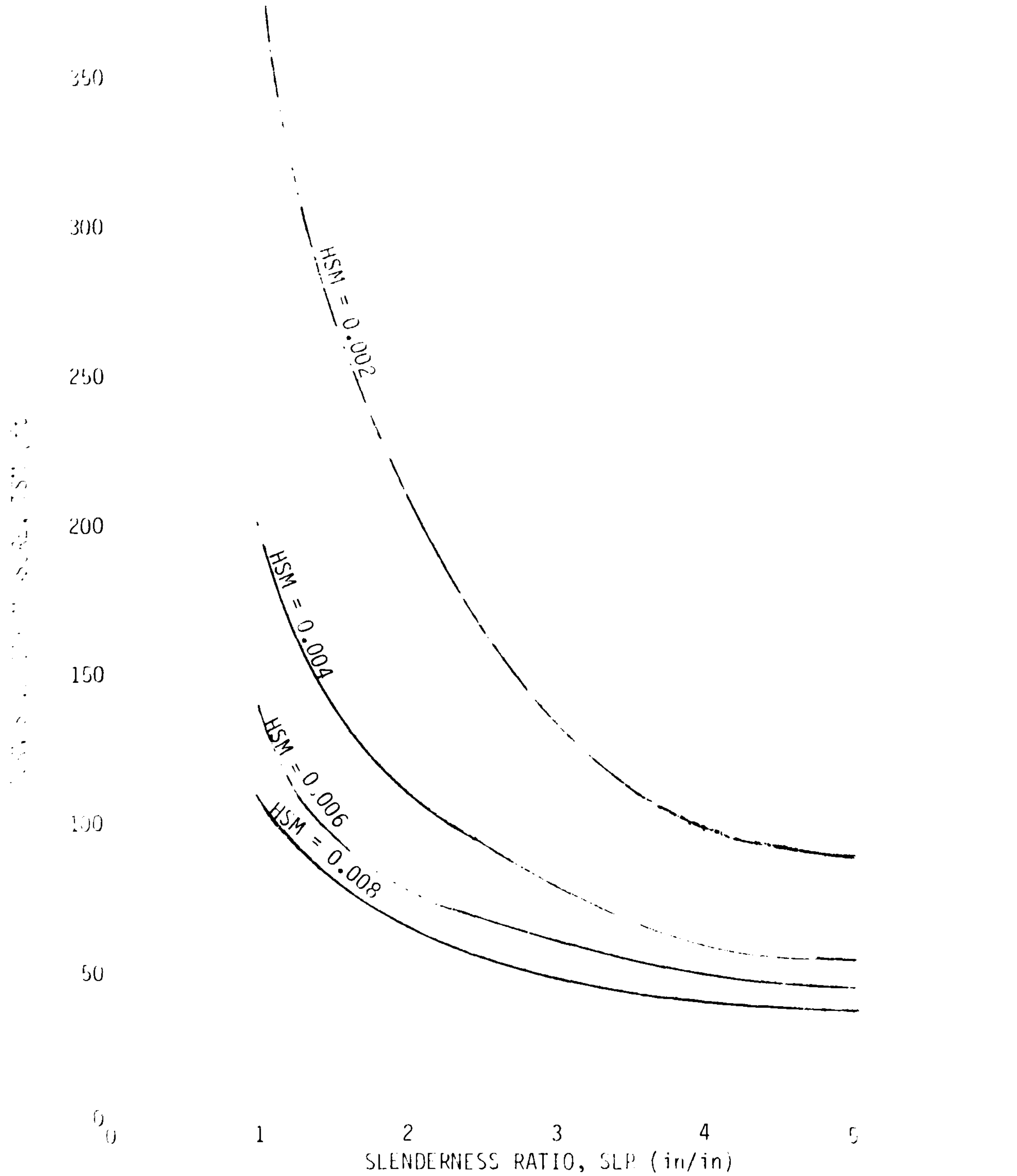


Figure 6 - 2

TURN SEVERITY MEASURE VERSUS SLENDERNESS RATIO AND HULL SHAPE MEASURE

Lateral Acceleration Predictor

The maximum lateral accelerations are experienced during the initiation of a turn. The steady state lateral acceleration can be used as a measure of the maximum acceleration. A predictor of the maximum acceleration is derived from the predicted maximum speed and the turn severity measure.

$$AP = V_m^2 / (TSM \times 32) \qquad (5)$$

where AP = acceleration predictor in g's

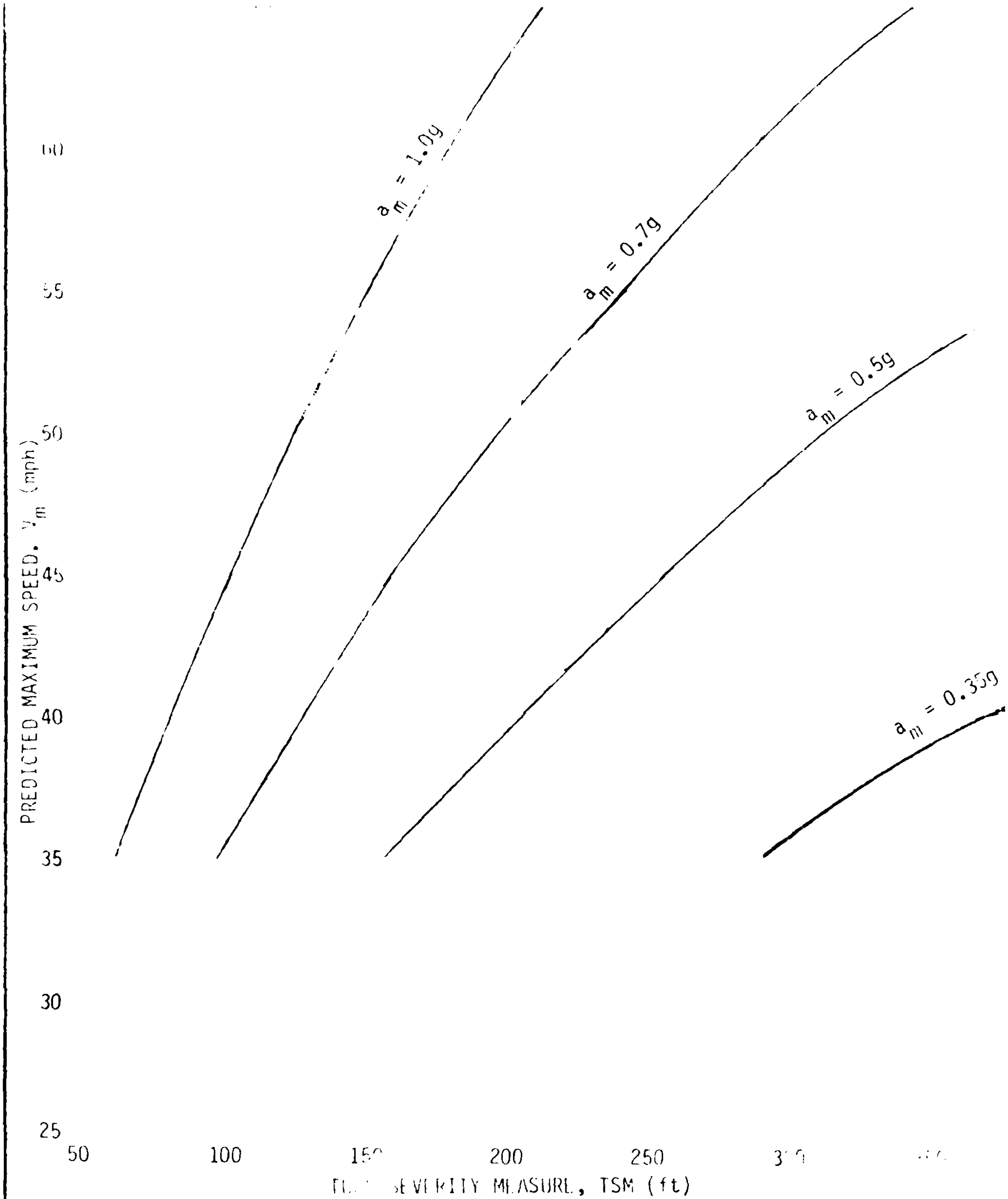
If the predictor is compared to the observed maximum lateral accelerations using a least square regression, the predictor is shown to be an excellent measure of observed accelerations.

$$a_m = 0.1795 + 1.3116\ AP \qquad (6)$$

where a_m = observed acceleration in g's

The coefficient of correlation is 0.9332 and the standard error of estimate is 5.13 percent. The acceleration predictor gives a very robust estimate of actual observed maximum lateral acceleration.

Figure 6-3 illustrates the use of the predicted maximum speed and the turn severity measure to evaluate the expected value of maximum lateral acceleration. The predicted maximum speed, V_m, is found from Figure 6-1. The turn severity measure, TSM, is found from Figure 6-2. The point on the acceleration chart in Figure 6-3 which is defined by V_m and TSM on the y-axis and x-axis respectively, gives the expected value of acceleration.



PREDICTED [illegible] ACCELERATION MEASURED BY
MAXIMUM [illegible] VERSUS TURN SEVERITY
Figure 6-3

EMPIRICAL VALIDATION

After the formulae to predict the magnitude of lateral acceleration for a boat/engine combination were developed, they were validated by comparing the results predicted through application of the formulae with the results observed during boat testing. Table 6-2, Predicted and Observed Variables, shows the results of this empirical validation, with predicted and observed values placed in adjacent columns.

Predicted/Observed Maximum Speed

The formula predicted maximum speed quite well for the boat/outboard motor combinations, with one exception, the Sterling with a 150 horsepower engine. Most speed predictions were within three miles per hour of observed values (less than six percent error). We do note that predicted speeds for the inboard/outboard boats were consistently higher than those that the boats actually achieved. We postulate that this is because the delivered horsepower of the boats is less than the rated horsepower. Only further analysis and testing can determine this.

Turn Severity Measure

The turn severity measure, an interim value required to calculate the predicted lateral accelerations, correlates fairly well with observed turning radii of the test boats. The measure tends to be lower than the actual turning radius; however, the observed turning radii vary enormously because they are so dependent upon environmental conditions and driver reactions. We observed that the turning radius of a boat/engine combination could vary up to 150 feet at ½ helm on one test run. Given the difficulty of prediction, the turn severity measure's degree of correlation is very encouraging.

Boat/Engine Combination	Predicted V_m (mph)	Observed V_m (mph)	Turn Severity Measure (ft)	Observed Turning Radius (ft)	Predicted Acceleration (g)	Observed ABYC Lateral Acceleration* (g)	Observed QT/TR Lateral Acceleration** (g)
Angler/115E	42.05	44	197.4	--	.547	.4 / .5 / .6	--
Angler/150M	45.47	51	177.4	282	.657	.35/ .6 / .8	.76
Bonito/55E	36.35	33	304.9	--	.357	.45/ 1.0 /1.4	1.5
Bonito/75E	39.80	36	295.3	269	.399	.18/ .43/ .65	.53
Caribe/198	47.98	39	109.2	120	1.044	.2 / 1.1 /1.75	1.39
Dolphin/200M	49.18	50.5	122.7	252	.987	--	--
Dolphin/235J	51.94	46	115.6	317	1.136	.2 / 1.0 /2.8	.79
Hawaiian/140	44.53	36.5	150(est)	202	.721	.3 / .67/1.0	.55
Higgscraft/150M	46.14	48.5	131.2	410	.8446	--	1.26
Higgscraft/200M	51.12	53	138.2	245	.955	.2 / .35/ .4	.9
Hydrasports/115E	43.26	46	312.3	--	.425	.32/ .45/ .57	.3
Hydrasports/150M	46.30	54	281.1	408	.499	--	.40
Sterling/150M	46.99	57	344.8	480	.4420	--	--
Sterling/235J	54.94	52	344.8	305	.539	.36/ .53/ .76	--

* Minimum, average, and maximum readings of maximum lateral acceleration
** Average maximum readings

Table 6 - 2

PREDICTED AND OBSERVED VARIABLES

Predicted/Observed Lateral Accelerations

The predicted and observed lateral accelerations are exceptionally close. In all instances, including the inboard/outboard data sets, predictions fall almost exactly on the average lateral acceleration values obtained during boat testing (ABYC tests and quick turn tests). The inboard/outboard boats are also predicted accurately probably because the inflated predictions are offset by inflated turn severity measures. For example, the Caribe's lateral acceleration is predicted to be 1.044g, and its observed average lateral acceleration in the ABYC test is 1.1g; the Hawaiian's predicted lateral acceleration is .721g and its observed lateral acceleration is .67g. Values for the outboard boat/engine combinations as a whole are almost exactly predicted by the formula (within five percent).

Lateral Acceleration Curves

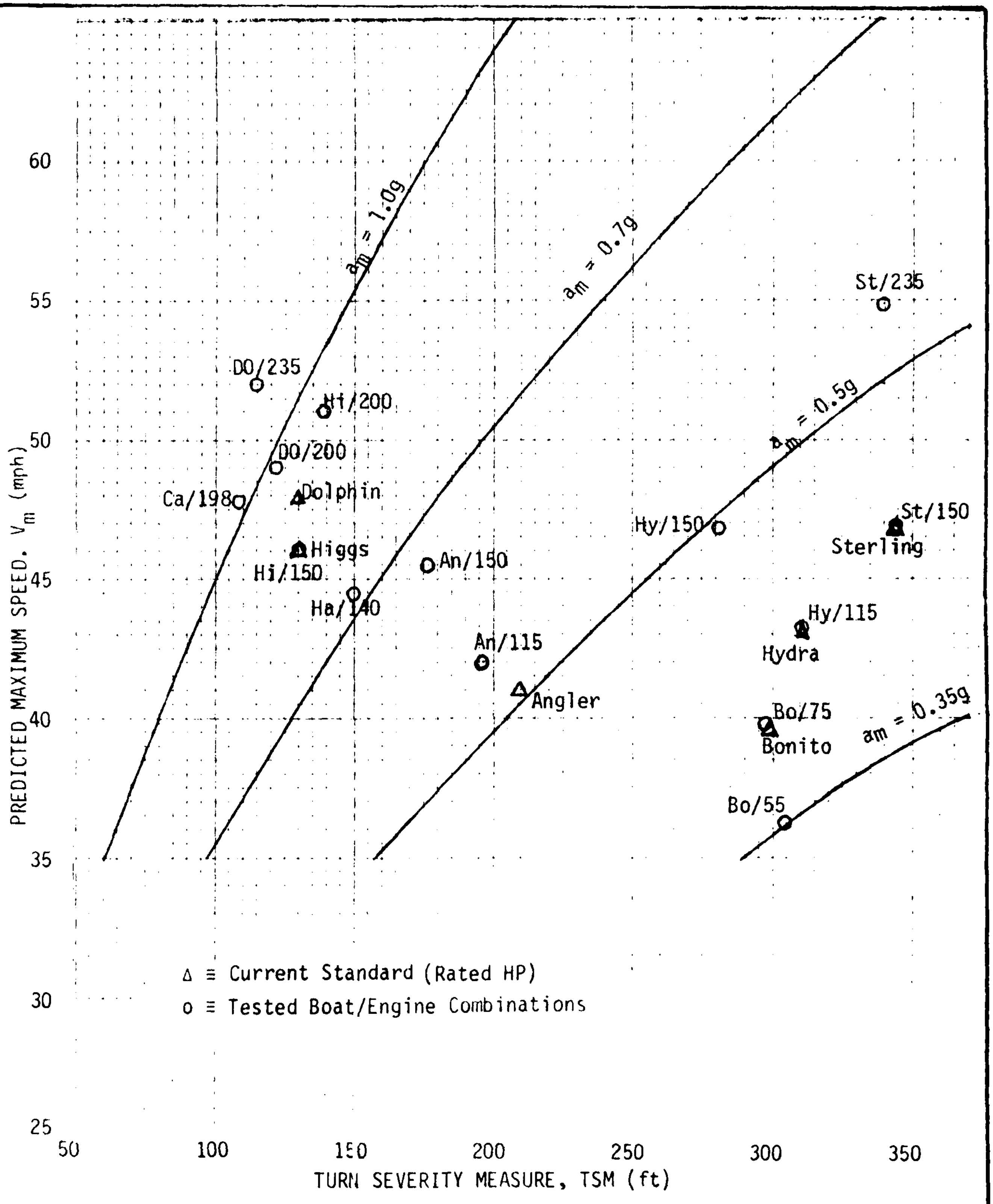
As the next step in its empirical validation effort, IDEAMATICS developed a set of curves using different lateral acceleration g levels. The levels chosen were based on the research on acceleration limits performed earlier in the project. We chose lateral acceleration levels of .35g, .5g, .7g, and 1g. The .35g curve represents a level slightly higher than the lateral acceleration at which public transit passengers begin to feel discomfort. The .5g curve represents a level at which unsupported seated and standing persons on board can be moved. The .7g curve represents a level at which supported and standing passengers will be moved, sometimes (as in the case of a transient acceleration) quite violently. The 1g curve represents an intolerably high lateral acceleration -- one which will limit the effective movement of both passengers and driver.

Figure 6-3 shows the lateral acceleration curves developed by IDEAMATICS. The lateral axis of the plot shows the turn severity measure (TSM) obtained through calculations using the slenderness ratio and the hull shape measure. The longitudinal axis shows the predicted speed in miles per hour. The curves show the increase in the TSM (i.e., the increase in the turn radius) as speed increases at a constant lateral acceleration. Figure 6-3 may be used as an analysis tool, since it graphically presents expected lateral accelerations of boat/engine combinations at maximum speed, and may also predict the expected maneuverability of the boat (i.e., its anticipated turning radius).

Boat Distribution Analysis

Figure 6-4 illustrates the use of the predicted acceleration curves as an analytical tool. Each boat/engine combination tested during the study is shown on the figure as a circle. The triangles present in Figure 6-4 indicate where the boats tested by IDEAMATICS fall on the set of curves given their present rated formula horsepower (calculations for these boats are presented in Table 6-3, Application of Formulae to Rated Boat/Engine Combinations).

The boats tended to cluster above the .7g curve (which is not surprising, since we intentionally overpowered the boats in our tests) and below the .5g curve. Overpowered boats stand in logical relationship to their position with rated horsepower. For example, the Higgscraft is rated for 150 horsepower. When the boat is run overpowered, with a 200 horsepower engine, higher g levels are predicted, along with a moderate increase in turn severity. The overpowered, "hot" boats are predicted to produce extremely high lateral accelerations and to be able to perform severe, low radius turns (which produce the high lateral accelerations).



PREDICTED LATERAL ACCELERATION MEASURED BY

MAXIMUM SPEED VERSUS TURN SEVERITY

Figure 6-4

Boat	Present Rated Horsepower	Estimated Total Weight in pounds	Beam at Chine in inches	Approximate Center of Gravity in inches	Deadrise in inches	Maximum Velocity in mph	Turn Severity Measure in degrees	Predicted Lateral Acceleration in g's
Angler	105	2700	63.25	65	13.5	41.33	217	.502
Bonito	70	2100	54.5	62	11	38.69	300	.384
Dolphin	185	2950	69.25	67	25	47.94	129	.913
Higgscraft	150	2683	71	55	16	46.14	131	.845
Hydrasports	120	2500	61.25	68	10	43.98	311	.434
Sterling	150	2544	72	67.5	8	46.99	345	.442

Table 6 - 3

APPLICATION OF FORMULAE TO

RATED BOAT/ENGINE COMBINATIONS

Those boats whose turn severity measure is high (i.e., their turning radius is predicted to be high) cluster between .5g and .35g. While the acceleration levels are acceptable, we suspect that these boats might not be as maneuverable as the boats with a smaller turn severity measure. Examining Table 6-4, Pass/Fail Results of ABYC Test, we see that the Sterling with a 150 horsepower engine and the Hydrasports with a 115 horsepower engine indeed failed the ABYC test one time each. However, this "maneuverability measure" must be used with caution, and must be tested with a greater sample than the 14 boat/engine combinations from the boat testing, since one boat (the Angler) which would be expected to pass the ABYC course on the basis of the formulae failed it miserably, and one boat (the Bonito) which would be expected to fail the course succeeded in all runs.

Caveats

Several caveats about the formulae must be expressed.

1. The sample against which the formulae have been validated is quite small, and further validation efforts against a larger universe must be performed.
2. Although the formulae predict lateral accelerations for the two inboard/outboard boats in our test sample very precisely, the maximum speed predicted is too high and turn severity measure is too great. The reasons for these discrepencies should be investigated.
3. The formulae work quite well in predicting lateral accelerations for most boats. However, in the case of the Bonito (a tri-hull), the lateral accelerations predicted are lower than those observed, and the turn severity measure is too high (thus indicating poor maneuverability when in fact it completed the ABYC course). It is possible that unusual hull shapes require additional work to validate the formulae.

SCENARIO EVALUATION

In scenario evaluation, IDEAMATICS pulled together the results of its research throughout the project, including the boat testing, PRAM analysis, and theoretical acceleration research, to evaluate what the boat performance predictions made by the formulae mean in terms of boating safety.

Boat/Engine Combination	Number of ABYC Tests	Number of Acceptable Tests	Number of Unacceptable Tests
Angler 115	9	5	4
Angler 150	9	8	1
Bonito 55	2	2	0
Bonito 75	6	6	0
Caribe 198	4	4	0 **
Dolphin 200	4	4	0
Dolphin 235	7	7	0
Hawaiian 140	7	7	0
Higgscraft 150	5	5	0
Higgscraft 200	2	2	0
Hydrasports 115	7	6	1
Hydrasports 150	6	6	0
Sterling 150	3	2	1
Sterling 235	2	2	0 *

* While the higher-powered Sterling passed its ABYC test, it did, in fact, swamp during the turn radius test

** The driver experience excessive force and was thrown into the windshield during these tests.

Table 6 - 4

PASS/FAIL RESULTS OF ABYC TEST

Lateral Acceleration Versus Maneuverability

Analysis of the PRAM data revealed that the greatest number of severe boating accidents involved falls overboard, and that maneuvering-related problems also were high on the list. Examining the boat testing results, especially the ABYC test course runs and the lateral accelerations measured during testing, it seems that a tradeoff between high lateral acceleration (which is a major contributing factor to falls overboard) and maneuvering ability (which effects accident avoidance) is involved. For example, the Caribe passed its ABYC test four times, with no failures. It is a maneuverable boat. However, our driver complained that he was being "knocked around" during the test course runs, and was thrown against the windshield on one run. The Caribe is predicted to generate 1.044g of lateral acceleration, and its average measured lateral acceleration was 1.1g, with a high value of 1.75g. Clearly, the Caribe is a boat that could throw a passenger overboard and that generates g forces so great the driver has difficulty functioning. Our test would fail the Caribe because it generates unacceptably high g forces (without the necessity of a dangerous test).

The Hydrasports' run with a 115 horsepower engine has a predicted lateral acceleration of .425 g and a measured lateral acceleration average (maximum) of .45g, with a high of .57g. These lateral accelerations are well within the acceptable range; they would move an unsupported passenger about, but would have little effect on supported passengers. However, the formulae predict that the Hydrasports/115 combination will have a high turn severity measure (i.e., will make large-radius turns). This seems to indicate that it is not a highly maneuverable boat. In fact, The Hydrasports/115 combination failed the ABYC test one time in seven while the Hydrasports/150 combination (still with acceptable lateral accelerations) passed the test with no failures.

This fact implies that the formulae can be used as predictors of a lower bound (acceptable maneuvering ability) as well as of an upper bound (unacceptable lateral accelerations). However, the lower bound must be used with great caution, and only after further research and validation studies have been performed.

Establishing Decision Criteria (Upper and Lower Bounds)

The IDEAMATICS formulae may be used to establish decision criteria for boat powering. The formulae are useful predictors of an upper bound, that of acceptable lateral accelerations. The idea of using the formulae to establish a lower bound (maneuverability) must be subjected to more testing and validation.

Maximum Acceleration: The Upper Bound

We propose the use of predicted maximum acceleration at maximum speed as the upper bound for establishing the maximum rated horsepower of a boat. The IDEAMATICS formulae predict maximum accelerations reliably, and the calculations used to predict the accelerations are easily made.

The difficulty is in establishing the acceleration value to be used as an upper bound. First, boat maneuverability must not be adversely affected. Boats which are able to perform fast emergency turns <u>will</u> generate relatively high lateral accelerations. Secondly, the boating public wishes to have fast, maneuverable boats, and would not accede to a standard that made for slow, placid boat/engine combinations.

IDEAMATICS believes that a .7g predicted maximum acceleration is a valid upper bound. Test boats clustering above .7g (all overpowered) performed well on the ABYC test course, but generated dangerously high average accelerations (including transient lateral accelerations above 1g). Setting

the standard any lower than .7g would probably mean great non-compliance from the boating public.

Maneuverability: The Lower Bound

Figure 6-4 hints that the IDEAMATICS formulae could be used to establish a lower bound for boat/engine combinations, that of expected turn severity. However, we present that as no more than a suggestion for further research and testing, since the measure is based on a small sample. One problem boat is the Bonito, predicted to have low maneuverability. In fact, it passed its ABYC test handily. However, the Bonito is a tri-hull, and its predicted performance and tested performance differ in other areas as well (e. g., its predicted acceleration is much lower than the measured accelerations). The anomalous maneuverability results probably have to do with the unusual hull shape.

Another problem boat is the Angler, predicted to be maneuverable. In fact, it failed the ABYC test with both test engines. The Angler's hull shape may account for a lower turn severity than anticipated with acceleration prediction (.547g predicted, versus .5g measured with the 115 horsepower engine, and .657g predicted versus .6g measured with the 150 horsepower engine.)

The use of predicted maneuvering ability as a lower bound is not recommended without further research and testing. However, it may be possible to apply the formulae to predict maneuvering ability. The practical lower bound on acceleration appears to be between .5g and .35g as shown by the tested boats.

FORMULAE APPLICATION TO PRAM DATA BASE

A powering formula can be demonstrated to be valid if that formula will accurately distinguish between "safe" and "unsafe" boats. The U.S. Coast Guard can obtain a measure of "unsafe" boats by examining the PRAM data base. A valid formula should predict whether or not those boats in PRAM will fail the maximum acceleration criterion.

IDEAMATICS Interim Report discussed in detail the PRAM data base and the reduction of the data to four accident types with five primary causes associated with twelve secondary causes.[3] Using this refined data base, the formulae have been applied to each category. For each category the mean value of the significant factors was used to calculate the average predicted values for maximum speed, turn severity and maximum acceleration. Table 6-5 summarizes these calculations. The consistency of the results confirms the hypothesis that the boats experiencing powering-related accidents are overpowered. Of the four accident types, three exhibit predicted accelerations of over 0.7g for the average boat involved in an accident (in addition, the average for the "falls overboard/falls within boat" of 0.68g is very close to the 0.7g limit).

The Interim Report identified that 73% of the fatal accidents occurred when the primary cause was attributed to "lateral acceleration." The predicted acceleration for all boats having accidents in the lateral acceleration category is 0.71g, clearly above the upper bound criterion.

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[3] IDEAMATICS, Inc., Interim Report on Development of Alternatives to the Current Safe Powering Standard, Volume I: Analysis, Appendix D, 17 November 1980, Washington, D.C., U.S. Coast Guard Report No. DTCG23-80-C-20003.

	Category	Number of Observations	Predicted Maximum Speed (mph)	Turn Severity Measure (ft)	Predicted Acceleration (g)
Accident Type	Collision/Grounding	30	51.1	151	0.89
	Swamp/Capsize/Flood/Sink	25	44.4	146	0.73
	Falls Overb/Falls within Boat	66	43.8	157	0.68
	Struck by Boat/Propellor	4	44.0	142	0.74
Primary Accident Cause	Lateral Acceleration	79	44.0	151	0.71
	Maneuvering--Collision	19	52.4	152	0.92
	Environment	11	46.9	149	0.78
	Velocity Change	14	42.3	168	0.62
	Other	2	48.9	148	0.84
Specific Accident Cause	Course Keeping	17	45.6	159	0.72
	Speed--While Turning	27	43.7	144	0.72
	Turn--POB Position	18	44.6	156	0.70
	Turn--Environment	14	42.7	154	0.67
	Other Dynamic Stability	3	37.9	138	0.61
	Failed Avoidance	18	52.9	153	0.93
	Combination, Speed and Weather	2	41.4	180	0.57
	Combination, Speed and Location	2	41.4	132	0.71
	Other Environment	7	48.9	155	0.81
	Start-in-Gear	6	42.8	177	0.60
	Sudden Surge	6	42.1	161	0.63
	Other Velocity Change	2	39.9	166	0.57

Table 6 - 5

APPLICATION OF FORMULAE TO PRAM BOATS GROUPED ACCORDING TO ACCIDENT TYPES AND ACCIDENT CAUSES

The applicability of the formulae is further illustrated when the secondary causes of the PRAM accidents are compared and contrasted. For example, we expect that if the cause is "speed-while-turning," then the accelerations will be excessive. Such is the case where the predicted acceleration for this secondary cause averages 0.72g. Alternatively, we expect that the "start-in-gear" secondary cause does not necessarily indicate overpowering or excessive accelerations. Therefore, the predicted value of 0.6g confirms our perception of the causative factor.

Review of the PRAM accidents and the predictive ability of the developed formulae indicate a high degree of reliability. The formulae, even in the present "rough" stage, will predict the expected accelerations and can be used to identify overpowered craft.

Potential Benefits

The value of any safe powering standard must be evaluated in terms of the benefits that can be derived by the application of the revised standard. In order to analyze the potential benefits of the proposed formulae, the PRAM accidents were reviewed in light of the affect of implementing the proposed approach. Table 6-6, Analysis of Benefits with PRAM Accidents, summarizes this review.

Using a criterion of 0.7g maximum predicted lateral acceleration, the PRAM accidents can be arranged by primary and secondary causation to identify those instances where such a criterion could have reduced and/or eliminated accidents. Table 6-6 assigns a potential level of high, medium and low to those cases where the criterion would have most likely reduced accidents, may have reduced accidents and probably would not have reduced accidents. Fifty-six percent of the 122 applicable PRAM accidents are

subject to a high potential for reduction based on a lateral acceleration criterion of 0.7g. Forty-six percent of the 72 fatalities fall within the category of high potential reduction. Similarly, 73% of the applicable PRAM accidents and 71% of the associated fatalities fall within the high and medium categories using such a criterion.

Therefore, the application of a lateral acceleration standard has a significant potential for reducing accidents and fatalities. Although further analysis and testing is required to validate the universal application of this hypothesis, there is a high probability that some non-trivial portion of the PRAM accidents and fatalities would have been averted if the lateral acceleration criterion had been in effect.

		Number of Accidents	Number of Fatalities	Predicted Acceleration (g)	Potential Reduction
Lateral Acceleration	Course Keeping	17	5	.72	High
	Speed--While Turning	27	24	.72	High
	Turn--POB Position	18	16	.70	Medium
	Turn--Environment	14	7	.67	Low
	Other Lateral Acceleration	3	2	.61	Low
Collision	Failed Avoidance	18	4	.93	High
Environment	Combination, Speed and Weather	2	1	.57	Low
	Combination, Speed and Location	2	2	.71	Medium
	Other Environment	7	0	.81	High
Velocity Change	Start-in-Gear	6	6	.60	Low
	Sudden Surge	6	3	.63	Low
	Other Velocity Change	2	2	.57	Low

ANALYSIS OF BENEFITS WITH PRAM ACCIDENTS

Table 6 - 6

CHAPTER VII

PROPOSED TECHNICAL APPROACH

The objective of the Current Safe Powering Study was to evaluate the feasibility of developing a revised standard and to propose an approach to advancing such a revised standard if feasible. This chapter presents a proposed technical approach for establishing a revised safe powering standard.

SCOPE OF APPROACH

The intent of a safe powering standard is to eliminate from the boating population boats which are unsafe due to excessive powering. The purpose of the standard is to reduce the number of accidents and the number of fatalities which are caused by overpowered boats. Any standard regulating power must recognize that it will not totally eliminate boating accidents. Other measures, such as increased education and more stringent enforcement, must be implemented to address accidents whose proximate cause(s) include improper operation. The powering standard addresses only those accident categories in which the proximate cause is the available (and thus utilized) power on a boat.

Powering-related accidents have been defined in this study as those accidents resulting from unnecessarily high/persistent cyclic forces, or lack of sufficient maneuverability. These are the criteria by which available power can be judged. The application of the criteria is dependent upon the desired level of regulation (e.g., how severe should controls be). Of these three criteria, the acceleration forces can be measured and evaluated objectively on an absolute scale.

The other two criteria -- cyclic forces and maneuverability -- can only be examined on a subjective basis through testing. The proposed technical approach must consider both.

FORMULA APPROACH

A formula approach is proposed for evaluating the acceleration forces anticipated from any specific boat/engine combination. As shown in Chapter VI, a rational formula can be postulated that predicts maximum acceleration from readily available parameters. The formula approach can be reduced to a graphical procedure for ease of promulgation and application. The approach has three steps as follows.

Parameter Measurement

The formula approach requires the measurement of actual boat and engine parameters. The following five parameters are proposed as the most significant.

- o engine horsepower
- o total loaded weight of the boat
- o maximum chine beam of the boat
- o distance from the transom to the loaded boat's center of gravity
- o deadrise angle at the transom

Variable Prediction

The maximum acceleration to be encountered during the normal operation of a boat/engine combination can be predicted from the five measured parameters. The predicted acceleration is based upon two intermediate predictors: maximum speed and turn severity. The formulae for these predictions are presented in Chapter VI.

Criterion Evaluation

The predicted acceleration must be evaluated against the criterion of acceptable maximum acceleration. An initial measure of acceptable accelerations can be 0.7g since it is the value above which supported sitting and standing passengers are subject to induced movement. An acceptable upper bound of .7g does not limit maneuvering ability or speed.

TEST COURSE APPROACH

A test course approach is proposed to evaluate the existence/non-existence of high/persistent cyclic forces, or the lack of adequate maneuvering ability. The present ABYC test course provides an excellent subjective evaluation of boat maneuvering ability when coupled with a rigorous objective measure of acceleration forces.

Not every boat/engine combination needs to be tested on a course. First, if the boat/engine combination has a predicted acceleration greater than the criterion (as calculated from the formula) then it need not be tested. Second, the test course will be used to evaluate the performance of a boat. Any acceptable mounted horsepower can be used to test the boat's performance. In other words, it is postulated that maneuvering ability and cyclic stability can be evaluated once for a boat design and does not require revalidation for alternative engines, provided those boat/engine combinations pass the formula criterion.

The test course approach consists of the present ABYC course evaluation. This approach is required only for a new boat (i.e., to test an introduced design). Previously tested boat designs do not require testing. Rather, only the formula need be applied to determine the acceptability of any proposed boat/engine combination.

SUMMARY OF PTA

The Proposed Technical Approach (PTA) is a two step process. The first step is to use the proposed formulae to evaluate boat/engine combinations in terms of acceptable accelerations. The second step is to use a test course to further evaluate specific boat performance in terms of maneuvering ability and cyclic instability. Once a particular boat has passed both steps successfully, subsequent boat/engine combinations need only be evaluated through the first step.

CHAPTER VIII

ADVANCED DEVELOPMENT PLAN

The advanced development plan presents the steps to be taken in moving from IDEAMATICS' study of alternatives to the current safe powering standard and proposed technical approach to a workable proposed standard for safe powering of small pleasure craft. The advanced development plan encompasses five steps:

- select a representative universe of boats and engines for further testing
- validate and possibly refine the predictive formulae
- assess the use of the formulae as a maneuvering ability predictor
- establish an upper limit for acceptable acceleration (and, possibly, a lower limit based on maneuvering ability)
- evaluate boat testing procedures

Each step is discussed in detail in the following sections of this chapter.

SELECTING BOATS FOR FURTHER TESTING

The boat/engine universe tested by IDEAMATICS was necessarily small. In order to validate the predictive formulae, and possibly refine them, a larger boat/engine universe will be required. As the first step in selecting boats and engines, analysts must determine the appearance of the universe: sizes of boats, hull shapes, and brands. This can be done through assessment of boating surveys done by the U.S. Coast Guard and through examination of samples of state boat registration data, if necessary.

Once the universe has been described, a representative boat/engine sample should be chosen. We recommend that this sample include:

- boats that have figured in PRAM accident cases involving falls overboard (73% of applicable accidents)

- a greater percentage of boats under 15 feet in length (underrepresented in IDEAMATICS' test sample)
- boats with complex hull shapes, particularly tri-hulls
- a small number of inboard/outboard boats
- engines of a sufficient horsepower range that boats can be tested slightly underpowered, at rated horsepower, and overpowered
- representation of all "standard" hull shapes
- representation of the full size range, from small to large

Such a sample will allow full validation of the predictive formulae developed by IDEAMATICS, including investigation of anomalous results possibly linked to hull shape (i.e., the low acceleration prediction for the Bonito).

VALIDATING AND REFINING THE PREDICTIVE FORMULAE

In order to validate the predictive formulae, predicted results must be compared with measured results for a representative sample of boats. Boat testing need address only values predicted by the formula, and boat measurements of only formula values need be taken. Three steps are required to fully validate the formulae: extensive validation, intensive validation, and formulae refinement.

Extensive Validation

During extensive formulae validation, the values for maximum speed, turn severity measure, and acceleration obtained by use of the predictive formulae will be compared with the values observed during testing. This will include:

- comparison of predicted/observed values for the entire test boat universe and calculation of degree of fit
- comparison of predicted/observed values obtained for different hull shapes, and further testing of hull shapes with relatively poor fit
- study of the effects of individual variables (e.g., maximum chinebeam) on the predicted results

Some of the boat/engine testing during the extensive validation phase will require testing on the water; however, this can be much simpler than the testing done by IDEAMATICS, since only a limited data set is required. The boats will have to undergo a maximum speed test, and run the ABYC course instrumented for acceleration.[1] These tests must examine known "safe" boats as well as known "unsafe" boats so that the versatility of the formulae can be demonstrated.

When the extensive validation effort has been performed, the U.S. Coast Guard will have ample data on the degree to which the formulae are accurate predictors of maximum speed, turn severity, and acceleration across a representative boat universe.

Intensive Validation

Intensive validation will measure the degree of applicability of the formulae to each type of boat. Tests are performed holding all parameters constant except for the single one under consideration. A uniform set of boat/engine combinations covering the full size range to be addressed by the standard will be tested, and predicted and observed values will be compared. This will allow determination of the formulae's responsiveness to size, weight, and center of gravity for a hull shape.

The objective of such testing is to evaluate the effect of modifying the significant parameters to reduce the scatter of the data (e.g., should deadrise angle be measured at the transom, at the center of gravity or at the maximum chine beam). This testing can possibly be performed at the David Taylor Model Basin.

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[1] It should be noted that a complete accelerometer study will not be needed for a great deal of the boat testing. Impact acceleration counters set at .5g, .7g, and 1g will be sufficient for much of the validation testing. This will reduce the complexity of the testing setup and will allow the testing of smaller boats that cannot handle the weight of the full instrumentation package.

Formulae Refinements

Working from the data obtained during the extensive and intensive validation, the formulae may be refined as needed to make them more accurate predictors. Possible refinements include modifying the factor which describes hull shape and modifying other input values to obtain a better fit (e.g., a factor to include propellor pitch in the horsepower specification).

ASSESSING THE USE OF THE FORMULAE TO PREDICT MANEUVERING ABILITY

Following the validation of the formulae, sufficient data will be available to assess the feasibility of using the formulae to predict maneuvering ability and establish a lower bound for boat/engine combinations. This will be done by careful examination of the predicted turn severity measure, the observed turning radii, and the pass/fail results of ABYC test course runs.

If it is decided to use the formulae to establish a lower bound on boat/engine combinations, that bound will be set during the next step of the advanced development plan, establishing limits.

ESTABLISH UPPER (AND, POSSIBLY, LOWER) LIMITS FOR ACCEPTABLE ACCELERATION

When validation and formulae refinement have established a satisfactory correlation between predicted and observed values for maximum speed, turning radius, and maximum acceleration, an upper bound (for acceleration) and a lower bound (for maneuverability) must be set. The upper bound will be the maximum predicted acceleration allowed; the lower bound will be the minimum maneuvering ability allowed.

Setting the bounds must take into account the tradeoffs between acceleration and maneuvering ability for accident avoidance. These bounds must consider the desires of the boating public and the likely degree of compliance with the standard as well as the effects of increasing g levels on boat passengers and drivers.

Once the standard has been set, the next step is to evaluate how best to test for compliance with the standard.

EVALUATING BOAT TESTING PROCEDURES

In this phase of the advanced development plan, boat testing procedures to ensure compliance with the standard will be evaluated. In particular, in order to reduce the testing burden on boat manufacturers, two assumptions must be examined:

- the boat need only be tested with one "valid" engine to determine that it has sufficient maneuverability and exhibits no cyclic instability
- instrumentation during testing can be reduced from a full accelerometer package to impact acceleration counters

Testing with One Valid Engine

Use of the predictive formulae will allow the calculation of a range of acceptable engine horsepowers for a particular boat. The burden on boat manufacturers would be substantially reduced if further testing for maneuvering ability and cyclic instability can be run with one engine determined to produce predicted accelerations within the acceptable range. This assumption must be evaluated using the data from the extensive and intensive validation testing performed earlier in the advanced development to determine whether any boat/engine combination falling within the formulae boundaries is acceptable in terms of acceleration without requiring individual testing.

Using Impact Acceleration Counters

The use of impact acceleration counters (i.e., devices that increment each time a certain acceleration is reached during a test run) would be advantageous in several ways: the reduced weight of the instrumentation package would allow the safe testing of smaller boats that cannot handle the weight of a full

instrumentation package, and the impact acceleration counters are relatively inexpensive and easy to use. Since during acceptance testing, only maximum accelerations are of interest, the use of these counters should present no problems. This assumption must be examined through study of results obtained during the validation phase using the impact acceleration counters.

Completion of the evaluation of boat testing procedures is the final step in advanced development of the safe powering standard.

CONCLUSIONS AND RECOMMENDATIONS

This section presents IDEAMATICS' conclusions and recommendations for continuing development of a safe powering standard for recreational boats.

CONCLUSIONS

IDEAMATICS' extensive study of alternatives to the current safe powering standard and development of a formulae to predict maximum accelerations have led to the following conclusions:

- o the formulae developed during the effort are good predictors of maximum acceleration
- o the formulae can possbily be used to predict maneuvering ability
- o the ABYC test course is a good measure of both lateral acceleration and maneuvering ability

RECOMMENDATIONS

IDEAMATICS recommends the following further activities in order to develop a workable standard for safe powering of recreational boats:

- o validation of the formulae through extensive testing against a large, representative sample of the boating universe

- study of the effects of hull shape on the predictive ability of the formulae
- assessment of the formulae as predictors of maneuvering ability
- establishment of a maximum horsepower standard based upon a criterion of maximum allowable accelerations
- assessment of required compliance testing

APPENDIX A

LIST OF MARINE ARCHITECTURE REFERENCES

LIST OF REFERENCES

Number	Title	Synopsis Enclosed

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APPENDIX B

CODING & ABBREVIATIONS

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		ALL CARDS
01-04	Boat number (BOATNO)	Number assigned by the Coast Guard to the boat. 1501 = Hydra-Sports 1517 = Dolphin 1503 = Hawaiian 1521 = Sterling 1510 = Bonito 1528 = Laminated 1514 = Angler 1531 = Higgscraft 1515 = Sportsman 1538 = Nuco/Caribe (Engine Description card does not carry this information)
05-08	Engine designation (EMAN + EHP)	Engine manufacturer's initial, followed by horsepower. E055 = Evinrude 55hp M150 = Mercury 150hp E075 = Evinrude 75hp M198 = Mercruiser 198hp E115 = Evinrude 115hp M200 = Mercury 200hp 0140 = Outboard Motor Co. 140hp J235 = Johnson 235hp (Boat Description card does not carry this information)
09	Run number (RUN)	Number of the appropriate testing run. (Engine Description card does not carry this information)
		CARD ONE: BOAT DESCRIPTION
10-13	Boat weight (BWT)	Weight of the boat hull in pounds.
14-18	Boat length (BLEN)	Length, in inches, of the boat cenerline (to the first decimal place).
19-22	Transom width (BTRWD)	Transom width in inches (to the first decimal place).
23-26	Transom height (BTRHT)	Transom height in inches (to the first decimal place).
27-30	Maximum capacity (BCAP)	Total weight, in pounds, that the boat can hold. (= People + gear.)

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
31-33	Rated hp (BHP)	Rated maximum horsepower.
34-35	Hull shape (BHSHP)	Boat hull shape. 0 = Deep-V 2 = Cathedral or tri-hull 1 = Semi-V 5 = Tunnel 6 = V
36-39	Degrees deadrise (BDEDRS)	Degrees deadrise at the transom (to the first decimal).
40-43	Transom angle (BTRANG)	Transom angle, in degrees, with respect to bottom.
44-47	Chinebeam (BCHINE)	Maximum beam, in inches, measured at the chine (to the first decimal).
48-51	Deadrise at maximum chine (BDRCHN)	Deadrise, in degrees, at the maximum chinebeam (to the first decimal).
52-55	Transom to maxchine (BLDIST)	Longitudinal distance, in inches, from the transom to the maximum chinebeam.
56	Steering (BSTEER)	Held for coded steering information.
57-58	Wheel diameter (BWHDIA)	Diameter, in inches, of the steering wheel.
59-61	Cable travel (BCABTR)	Inches the steering cable travels per 360 degrees.
62	Controls (BSTCTL)	Held for coded steering control information.
63-66	Engine height (BHTENG)	Height, in inches, of the engine (to the first decimal).
67-70	Cavitation plate (BCAV)	Angle, in degrees, of the cavitation plate relative to the transom when parallel to the bottom (to the first decimal).
71-74	Trim angle (BTRIM)	Trim angle, in degrees (to the first decimal).
75-78	-blank-	-blank-
79-80	Card number	01 (the number of all boat description cards).

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		CARD TEN: ENGINE DESCRIPTION
01-04	-blank-	-blank-
05-08	Manufacturer and horsepower (EMAN, EHP)	Name of manufacturer and amount of horsepower.
09	-blank-	-blank-
10-13	Shaft length (ESHLEN)	Engine shaft length, in inches (to the first decimal).
14-19	Weight (EWEIGHT)	Weight of engine, in pounds (to the first decimal).
20	Material (EMAT)	Material propellor is constructed from. A = aluminum
21	Blades (EBLADE)	Number of propellor blades.
22-25	Diameter (EPROPD)	Propellor diameter, in inches (to the first decimal).
26-29	Pitch (EPROPP)	Propellor pitch (to the first decimal).
30	Exhaust (EEXST)	Propellor exhaust: hub(H) or non-hub (N).
69-70	Card number	10 (the number of all engine description cards).
		CARD TWO: SPEED TEST
01-09	Repeated info. (BOATNO, EMAN, EHP, RUN)	Boat number, engine, and run.
10-11	Maximum speed-max (SPDMAX)	Maximum speed reached at maximum trim.
14-15	Planing speed-max (SPLMAX)	Planing speed at maximum trim.
18-19	Maximum speed-ave (SPDAVE)	Maximum speed reached at average trim.

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		CARD TWO: SPEED TEST (cont.)
22-23	Planing speed-ave. (SPLAVE)	Planing speed at average trim.
26-27	Maximum speed-und (SPDUND)	Maximum speed reached under trimmed.
30-31	Planing speed-und (SPLUND)	Planing speed when under trimmed.
34-35	Porpoising count (PORPCT)	Porpoising count (at maximum trim).
38-39	Porpoising speed (SPORP)	Speed at which porpoising occurs (at maximum trim).
42-43	Center of gravity (BLCG)	Distance, in inches, from the transom to the boat's center of gravity.
79-80	Card number	02
		CARD THREE: ABYC TEST I
01-09	Repeated information (BOATNO, EMAN, EHP, RUN)	Boat number, engine, and run.
10-11	Speed in (ASPDIN)	Speed at which boat is traveling when it enters the ABYC course.
12-13	Speed out (ASPOUT)	Speed at which boat is traveling when it leaves the course.
14-15	Direction (ADIR)	Direction of test: East-West or West-East.
16	Acceptability (ACTEPT)	Acceptability of boat performance, yes or no.
17-21	Acc.-longi/turn (ALONT)	Longitudinal acceleration at the turn. (All accelerations are expressed in g's, to the second or third decimal point.)
22-26	Acc.-longi/off (ALONO)	Longitudinal acceleration at offset.
27-31	Acc.-longi/ret. (ALONR)	Longitudinal acceleration at return.

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		CARD THREE: ABYC TEST I (cont.)
32-36	Acc.-vert/turn (AVERT)	Vertical acceleration at the turn.
37-41	Acc.-vert/off (AVERO)	Vertical acceleration at offset.
42-46	Acc.-vert/ret. (AVERR)	Vertical acceleration at return.
47-51	Acc.-lat/turn (ALATT)	Lateral acceleration at the turn.
52-56	Acc.-lat/off (ALATO)	Lateral acceleration at offset.
57-61	Acc.-lat/ret. ALATR)	Lateral acceleration at return.
62-63	Test number (TESTNO)	Number of the test within the sequence of this run.
79-80	Card number	03
		CARD FOUR: ABYC TEST II
01-09	Repeated information (BOATNO, EMAN, EHP, RUN)	Boat number, engine, and run.
14-15	Direction (ADIR)	Direction of test: East-West or West-East.
17-21	Acc.-bow/turn (ABOWT)	Bow acceleration at the turn.
22-26	Acc.-bow/off (ABOWO)	Bow acceleration at offset.
27-31	Acc.-bow/ret. (ABOWR)	Bow acceleration at return.
32-36	Acc.-seat/turn (ASEATT)	Seatpad acceleration at the turn.
37-41	Acc.-seat/off (ASEATO)	Seatpad acceleration at offset.
42-46	Acc.-seat/ret. (ASEATR)	Seatpad acceleration at return.

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		CARD FOUR: ABYC TEST II (cont.)
62-63	Test number (TESTNO)	Number of the test within the sequence of this run.
79-80	Card number	04
		CARD FIVE: TURN TESTS I
01-09	Repeated information (BOATNO, EMAN, EHP, RUN)	Boat number, engine, and run.
10-11	Test type (TSTTYP)	Test type: Quick turn (QT) or Turn Radius (TR).
12-13	Test number (TNUMB)	Number of the test within the sequence of this run.
14-16	Direction (TDR)	Direction of the turn: clockwise (CW) or counter clockwise (CCW).
17-19	Helm change (THELM)	Amount helm (steering wheel) is turned (.25, .50, or .75).
20-21	Speed in (TSPDIN)	Speed at which boat is traveling when turn is initiated.
22-23	Speed out (TSPDOT)	Speed at which boat is traveling when 360^{o} completed.
24-26	Radius (TRAD)	Radius of the turn.
27-30	Acc.-long./plus (TLNMXP)	Longitudinal acceleration, maximum, plus values.
31-34	Acc.-long./minus (TLNMXM)	Longitudinal acceleration, maximum, minus values.
35-38	Acc.-vert./plus (TVRMXP)	Vertical acceleration, maximum, plus values.
39-42	Acc.-vert./minus (TVRMXM)	Vertical acceleratin, maximum, minus values.
43-46	Acc.-lat./plus (TLTMXP)	Lateral acceleration, maximum, plus values.
47-50	Acc.-lat./minus (TLTMXM)	Lateral acceleration, maximum, minus values.

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		CARD FIVE: TURN TESTS I (cont.)
51-54	Acc.-bow/plus (TBWMXP)	Bow acceleration, maximum, plus values.
55-58	Acc.-bow/minus (TBWMXM)	Bow acceleration, maximum, minus values.
59-62	Acc.-seat/plus (TSTMXP)	Seatpad acceleration, maximum, plus values.
63-66	Acc.-seat/minus (TSTMXM)	Seatpad acceleration, maximum, minus values.
67-68	Motor angle (TMTANG)	Motor turn angle, in degrees.
69-72	Turn time (TTIME)	Time elapsed.
79-80	Card number	05
		CARD SIX: TURN TESTS II
01-09	Repeated information (BOATNO, EMAN, EHP, RUN)	Boat number, engine, and run.
10-11	Test type (TSTTYP)	Test type: Quick Turn (QT) or Turn Radius (TR).
12-13	Test number (TNUMB)	Number of the test within the sequence of this run.
27-30	Acc.-long./plus (TLNSSP)	Longitudinal acceleration, steady state, plus values.
31-34	Acc.-long./minus (TLNSSM)	Longitudinal acceleration, steady state, minus values.
35-38	Acc.-vert./plus (TVRSSP)	Vertical acceleration, steady state, plus values.
39-42	Acc.-vert./minus (TVRSSM)	Vertical acceleration, steady state, minus values.
43-46	Acc.-lat./plus (TLTSSP)	Lateral acceleration, steady state, plus values.
47-50	Acc.-lat./minus (TLTSSM)	Lateral acceleration, steady state, minus values.

Column(s)	Variable Name	DESCRIPTION; CARD NUMBER AND NAME
		CARD SIX: TURN TESTS II (cont.)
51-54	Acc.-bow/plus (TBWSSP)	Bow acceleration, steady state, plus values.
55-58	Acc.-bow/minus (TBWSSM)	Bow acceleration, steady state, minus values.
79-80	Card number	06
		CARD SEVEN: ZIG ZAG TEST
01-09	Repeated information (BOATNO, EMAN, EHP, RUN)	Boat number, engine, and run.
10-11	Test number	Test number within the sequence of this run.
12-15	Time from start	Number of seconds from the start of of the test (light or previous motor angle) to the next motor angle change.
16-17	Motor angle	Angle, in degrees, motor is turned.
18	Direction	Direction in which motor is turned: Left (L) or Right (R).
19-22	Time to change	Amount of time it takes for the motor to change from one heading to the next.
23-26	Heading change	Number of degrees the compass rotates after motor is turned until next motor turn.
27-28	Turn number	Number of this turn within the sequence of this test.
79-80	Card number	07

APPENDIX C

VARIABLES GENERATED AND ABBREVIATIONS

VARIABLES GENERATED AND ABBREVIATIONS

Variables

ACCELP = acceleration indicator
= SPDSQR/(STDTRAD * 32)

BEAMLD = beamload
= 27.6923 * TWT/(BCHINE**3)

BLCGCH = longitudinal center of gravity over chine width
= BLCG/BCHINE

CROUCH = Crouch number
= SPDMAX * (HPLOAD**0.5)

FACT2 = revised formula
= BLCG * BCHINE/72

FATRAT = fatness ratio
= .33053 * BCHINE/(TWT**0.3333)

FORMFACT = present formula factor
= BLEN * BTRWD/72

HPLOAD = ratio of total weight to engine horsepower
= TWT/EHP

PSBLOC = pseudo Block number
= 55.3846*(TWT/(BLEN*BCHINE**2*TAN (BDEDRS/(3.1416/180))))

SLENDRAT = slenderness ratio
= .33053 * BLEN /(TWT**0.3333)

SLENDRAT2 = recalculated slenderness ratio
= .33053 * BLCG /(TWT**0.333)

SPDCOEFF = speed coefficient
= .8954 * SPDMAX / (SQRT(BCHINE))

SPDSQR = maximum speed squared
= (SPDMAX * 5280/3600) ** 2

SPECREST = specific resistance
= 375.0*EHP/ (TWT*SPDMAX)

STDTRAD = standardized turning radius
= TRAD * TMTANG / 10

TRADHLF = turning radii resulting from half helm turn

TRADQTR = turning radii resulting from quarter helm turn

TRAD3QTR = turning radii resulting from three-quarter helm turn

TWT = total weight (boat plus engine plus driver plus gear)
= BWT + EWEIGT + 400

VOLFROD = volumetric Froude number
= .5148 * SPDMAX /(TWT ** 0.16667)

Card # 1, Boat Description

BOATNO = boat number
BWT = boat weight
BLEN = boat length
BTRWD = transom width
BTRHT = transom height
BCAP = maximum capacity (how much is it rated to hold)
BHP = rated horsepower
BHSHP = hull shape
BDEDRS = deadrise
BTRANG = transom angle
BCHINE = maximum chine
BDRCHN = deadrise at maximum chine
BLDIST = longitudinal distance from transom to maximum chine
BSTEER = steering
BWHDIA = steering wheel diameter
BCABTR = inches steering cable travels per 360 degrees
BSTCTL = steering controls
BHTENG = height of engine
BCAV = cavitation plate relative to transom when parallel to bottom
BTRIM = trim angle

Card # 10, Engine Description

EMAN = manufacturer
EHP = horse power of engine used in test
ESHLEN = engine shaft length
EWEIGHT = engine weight
EMAT = propellor material
EBLADE = number of propellor blades
EPROPD = propellor diameter
EPROPP = propellor pitch
EEXST = propellor exhaust (hub or non-hub)

Card # 2, Speed Test

SPDMAX = maximum speed, maximum trim
SPLMAX = planing speed, maximum trim
SPDAVE = maximum speed, average trim
SPLAVE = planing speed, average trim
SPDUND = maximum speed, under trim
SPLUND = planing speed, under trim
PORPCT = porpoising count (at maximum trim)
SPORP = porpoising speed (at maximum trim)

Cards #3 + 4, ABYC Test

ASPDIN = speed in
ASPOUT = speed out
ASPDLST = speed lost during test
ADIR = direction of test
ACTEPT = acceptability
ALONT = longitudinal acceleration at turn
ALONO = longitudinal acceleration at offset
ALONR = longitudinal acceleration at return
AVERT = vertical acceleration at turn
AVERO = vertical acceleration at offset
AVERR = vertical acceleration at return
ALATT = lateral acceleration at turn
ALATO = lateral acceleration at offset
ALATR = lateral acceleration at return
TESTNO = test number
ABOWT = bow acceleration at turn
ABOWO = bow acceleration at offset
ABOWR = bow acceleration at return
ASEATT = seatpad acceleration at turn
ASEATO = seatpad acceleration at offset
ASEATR = seatpad acceleration at return

Cards #5 + 6, Quick Turn and Turn Radius Tests

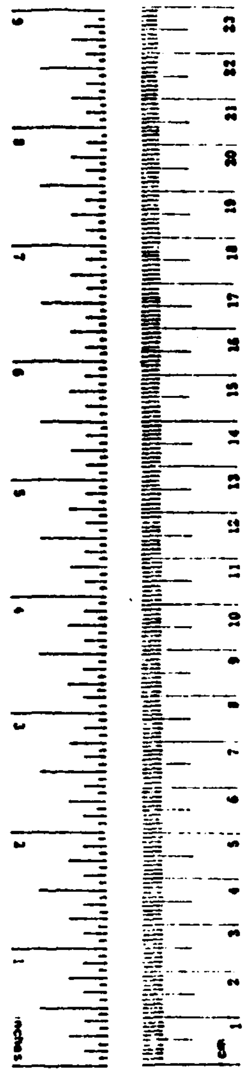
TSTTYP = test types (quick turn or turn radius)
TNUMB = test number
TDR = turn direction (clockwise or counterclockwise)
THELM = helm change (1/4, 1/2, 3/4)
TSPDIN = speed into turn test
TSPDOT = speed out of turn test
TSPDLST = speed lost during turn test
TRAD = turn radius
TLNMXP = longitudinal acceleration, maximum, plus values
TLNMXM = longitudinal acceleration, maximum, minus values
TVRMXP = vertical acceleration, maximum, plus values
TVRMXM = vertical acceleration, maximum, minus values
TLTMXP = lateral acceleration, maximum, plus values
TLTMXM = lateral acceleration, maximum, minus values
TBWMXP = bow acceleration, maximum, plus values
TBWMXM = bow accleration, maximum, minus values
TMTANG = motor turn angle
TTIME = time elapsed
TLNSSP = longitudinal acceleration, steady state, plus values
TLNSSM = longitudinal acceleration, steady state, minus values
TVRSSP = vertical acceleration, steady state, plus values
TVRSSM = vertical acceleration, steady state, minus values
TLTSSP = lateral acceleration, steady state, plus values
TLTSSM = lateral acceleration, steady state, minus values
TBWSSP = bow acceleration, steady state, plus values
TBWSSM = bow acceleration, steady state, minus values

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

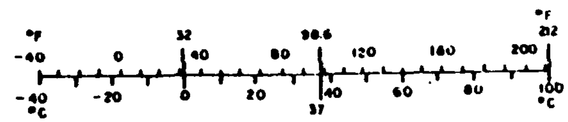
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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